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A VIRTUAL MACHINING MODEL FOR SUSTAINABILITY ANALYSIS

Guodong Shao, Deogratias Kibira, and Kevin Lyons
Manufacturing Systems Integration Division
National Institute of Standards and Technology
Gaithersburg, Maryland 20899
U.S.A.

ABSTRACT

Sustainability has become a very significant research topic since it impacts many different manufacturing industries. The adoption of sustainable manufacturing practices and technologies offers industry a cost effective route to improve economic, environmental, and social performance. As a major manufacturing process, the machining system plays an important role for sustainable manufacturing on the factory floor. Therefore, technologies for monitoring, analyzing, evaluating, and optimizing the sustainability impact of machining systems are critical for decision makers. Modeling and Simulation (M&S) can be an effective tool for success of sustainable manufacturing through its ability to predict the effect of implementing a new facility, process without interrupting real production. This paper introduces a methodology that provides a traditional virtual Numerical Control (NC) machining model with a new capability – to quantitatively analyze the environmental impact of machining system based on Life Cycle Assessment (LCA). The objective of the methodology is to analyze the sustainability impacts of machining process and determine a better plan for improving the sustainable performance of machining system in a virtual environment before work orders are released to the shop floor. Testing different scenarios with simulation models ensures the best setting option available can be chosen. The virtual NC model provides the necessary data for this assessment. In this paper, a list of environmental impact indicators and their metrics has been identified, and modeling elements for sustainable machining have been discussed. Inputs and outputs of the virtual machining model for sustainable machining are described. A case study to experiment the proposed methodology is discussed.

INTRODUCTION

This section describes the concept of sustainable manufacturing, sustainable machining, Modeling and Simulation (M&S), and Life Cycle Assessment (LCA). Current problems in industry are also addressed.

Sustainable Manufacturing

Sustainable development has become an important part of approaches to integrate economic, environmental, and social aspects. The Department of Commerce recently identified sustainable manufacturing as one of its high-priority performance goals, defining sustainable manufacturing as the "*creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound* [1]." As such, sustainability related issues such as energy consumption, emissions and other environmental impact issues are becoming a more integrated part of operational and long-term planning decisions in manufacturing [2]. Machining is a major manufacturing operation and it involves a number of sustainability factors that have a big potential for environmental impact. These factors include tool life, usage of coolant and lubricant, waste chips and energy consumption. Therefore, the analysis of machining systems and optimization of these input factors (controls and constraints) and outputs (objective functions) has significant implication for sustainable manufacturing. It has been observed that the relationship between machining technologies and environmental impact remains insufficiently discussed and the environmental impact due to this manufacturing activity has been little evaluated [3]. Currently, there is no ideal method that can analyze the environmental impact of machining processes systematically to predict the outcome of the machining operations and optimize the process. This paper is a step towards to this direction.

Modeling and Simulation for Manufacturing

M&S has been proven to be an effective tool for reducing costs, improving quality, and shortening the time-to-market for products in the manufacturing industry. The virtual machining models simulate the kinematics, dynamic, mechanical, control, other behavioral characteristics of machining system. A virtual machining model allows visualizing and analyzing the functionality of a machine tool, the machine's Computer Numerical Controlled (CNC) controller, and the material removal process. It can be used for emulating, validating, and optimizing the NC machine processes. The virtual environment enables the engineers to perform program prove-outs off line, while keeping the actual machine tool in production and avoiding expensive machine down time and possible tool crashes. It can also be used to evaluate machine tool's capabilities and setups, debug, and test new post-processors, design fixtures, determine the best suited machine tool for a given job, and detect near misses and collisions. It is also useful for process evaluation of the conditions that cause cutter and tool breakage, or gouges and undercuts. The analysis of data collected during the machining cycle is used to optimize the program cycle time, tool life, and surface finish. Using a virtual machining model, all experiments can be performed in a safe environment [4].

Likewise, M&S will be an essential ingredient for sustainable machining through its ability to predict the effect of implementing certain facility, process and product actions and analyzing the environmental impacts. Kibira and McLean have developed a vision for M&S of sustainable manufacturing [5]. However, little work has been done to incorporate sustainability indicators in simulation models. It is especially important if the current existing virtual machining model can be extended to include the new functionality of sustainability analysis. Since there has not much demand for simulation technology to deal with sustainability features, software vendors and analysts have not typically addressed these issues. Therefore, models for sustainable manufacturing have to be built using existing simulation engines. The new aspect greatly complicates the simulation modeling. But with a systematic approach, the sustainability impacts of machining system and production process can be incorporated and evaluated.

Life Cycle Assessment Methods

Life Cycle Assessment (LCA) is a very useful methodology for analyzing sustainability of manufacturing systems, using multiple commensurable (i.e., measurable in similar units) aspects of quantifiable systems, based on systems thinking. Normally, LCA methods analyze parameters such as energy, resources, impact and outputs, e.g., waste, emissions, electricity, and total energy. The results from this analysis provide guidance on the relative impacts of different types of products, materials, services, or industries with respect to resource use and emissions throughout the supply chain. For example, the effect of producing an automobile would include not only the impacts at the final assembly facility, but also the impact from mining metal ores, making electronic parts, forming windows, etc. that are needed for parts to build the car [6].

The simulation of machining operations in combination with LCA and sustainability related data can be utilized to estimate the environmental performance measures of a machining system. The improvement of such performance measures includes optimizing material use, minimizing the use of cutting fluids, and reducing cutting energy [7].

This paper proposes a methodology that uses a virtual model of a machining system to analyze the environmental impact of the process. The objective of simulation system, scope, model elements, and its input and output requirements are discussed. This approach allows assessing the environmental impact in the virtual environment using real world data, specification data, and simulation data as input and providing a platform to evaluate different options for an optimal decision making.

The paper is subdivided into five main sections. The next section discusses related work, followed by the introduction of the proposed methodology. Then the procedure of a potential case study is described to test the methodology. Finally, a summary is provided and future work is discussed.

RELATED WORK

This section discusses the related research work, techniques, and tools for the proposed methodology. Even though sustainable machining is crucial to sustainable manufacturing in shop floor operations, there is still insufficient research performed on this topic [3]. The approaches to solve the problem vary from finding alternative material removal methods to changing of material to optimization of the various inputs to machining process. The main objective of published research listed in the reference is to optimize environmental factors such as the usage of material, cutting fluids, and energy. Alternative material removal technologies include cryogenic machining and high pressure assisted machining, as opposed to conventional machining, that are deemed to be more environmental friendly for machining of materials with unique thermo-mechanical properties such as Nickel and Titanium alloys [8].

Environmental consideration of machining

Optimization of process parameters introduced in [9] analyzes the environmental impact of turning operation of American Iron and Steel Institute (AISI) 1040 Steel. This analysis is based on using sensors and instruments on the machine tools and calculation – along four indicators (global warming, acidification, eutrophication, photo-chemical oxidant) for machining operations. It proposes using already existing technology while choosing the best process parameters and practices. A general description of approaches that can reduce environmental burden is presented in [10]; the authors describe different approaches involving design for sustainability, developing sustainable production management systems, and alternative machining processes. Another research conducted environmental analysis of machining operations from a systems perspective [7]. In this approach, the work focuses on minimizing environmental impact of machining and associated activities such as tool preparation, material production, material removal, and cleaning among others. This analysis aims to determine a distribution of energy usage through various activities. Akbari and others carry out the lifecycle of machine tools from manufacture, use to disposal. During operation it is found that more energy can actually be used for running peripheral devices such as coolant pump, hydraulic pump, and control devices than actual cutting [11]. [12] describes a methodology using an environmental-based process model for computing energy use and wastes in addition to traditional parameters like process time and yield of a product design to facilitate systems planning for machining operations. [13] proposed a generic energy consumption model that can be applied to describe how the energy consumption and the energy efficiency of machines and production systems relates to the way they operated.

Simulation methods for sustainability analysis of machining

Narita and others developed a machining simulator, which consists not only of the simulation of the production of the geometry of the product but also the physical system to extract information such as energy consumption, coolant, and lubricant used [14]. An extension of previous methods that evaluate the difference between dry, minimal quantity lubricant (MQL), and wet machining approaches and include such factors as depth of cut, feed rate, spindle speed, and tool path pattern to find one with the least environmental burden of a machine tool operation has been developed [15]. The environmental burden is calculated after converting all the measures to CO_2 equivalent. Narita and Fujimoto developed algorithms to calculate the “environmental burden” due to machine tool operations. They calculated the environmental impact of dry, MQL, and wet machining on the five impacted categories of global warming, acidification, eutrophication, photochemical oxidants, human toxicity, and ecotoxicity [3]. In another approach a prediction system based on LCA is used where “environmental burden” is evaluated using the inputs: workpiece model, cutting tools model and NC program while inputting information associated with the machine tool and machining process. Then the electric power consumption, cutting tool status, coolant quantity, lubricant oil, metal chips, and other factors can be calculated [16].

In general, the sustainable machining research was carried out in an ad hoc and piecemeal manner without methodology to systematically consider available model and data and guide decision making to optimize machining operations for minimal environmental impact in a virtual environment. This paper proposes such a methodology.

PROPOSED METHODOLOGY

Based on the needs described in previous sections, an innovative methodology that proposes procedures to allow the modeling, simulation, and analysis of sustainability indicators is introduced. It is described in the following subsections.

Procedures

The methodology involves several activities as shown in Figure 1. It includes defining a problem, setting up objectives of the study, selecting software, identifying modeling methods, developing model, executing the model, and analyzing the simulation results. The detailed steps are list below.

1. Define a machining problem by setting up a set of objectives and scope
2. Identify the key performance indicators that includes sustainability indicators and their metrics for machining processes
3. Create the virtual machining model, that is, to develop a simulation model of the machine tool under study
4. Define a test part for the study
5. Develop models of workpiece, fixtures, and cutting tools
6. Identify and develop the model for each sustainable indicator such as energy consumption
7. Collect the relevant data from a real machine if necessary
8. Collect data from the machine specification
9. Collect data from the LCA database
10. Develop methods to extract intermediate data from the virtual machining model
11. Process the raw data to extract the useful subset for modeling purpose
12. Format and input appropriate sustainability data according to the input data requirement of the simulation software
13. Create test scenarios
14. Execute the NC program in the virtual environment
15. Generate simulation results that include virtual part and NC validation report
16. Modify NC program if necessary
17. Repeat step 14 until the NC is validated
18. Generate sustainability report by executing the correct NC program
19. Analyze the key sustainability performance indicators such as total emission

Some of steps such as step 3 to step 5 are the typical steps in current machining simulation. To simulate and analyze the sustainable machining, extra work is required, e. g., steps 2, 6, 9 are specifically for sustainable machining. Figure 1 shows main modeling procedure of the proposed methodology. In order to successfully perform the sustainability analysis using the methodology, the following questions need to be answered: How can the sustainable indicators be integrated with the virtual machining model? What role does tool wear play for environment impact? What real machine data needs to be collected? What data needs to be collected from the specifications? What data needs to be collected from LCA database? In what format is the collected data presented? How should the data be processed? How can the data needed from virtual machining model be expressed?

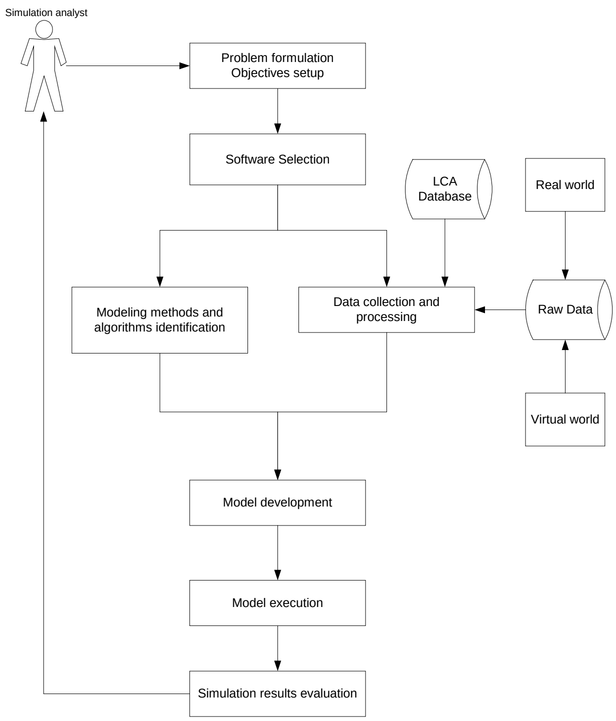

Figure 1. Modeling procedures in the proposed methodology

System Boundaries

As mentioned earlier, [7] suggested that the environmental analysis of machining operations should start from a systems perspective. We need to clearly define the system boundary/scope of the proposed methodology. The machining system as a whole includes activities such as tool preparation, material preparation, material handling, material removal, tool changing, cooling, cleaning, and chips conveyor. The dotted area in Figure 2 shows the components of interest for the proposed methodology. We focus on the elements within the boundary because it is central to machining operations, from which sustainability data can be collected and needs to be analyzed. It is also the scope of a virtual machining model.

Sustainability Performance Analysis Using Virtual Machining Model

A virtual machining model is an interactive 3D computer simulation model. The main purpose of using a virtual machining model early in the planning stage for machining process is to improve part quality, to save time and money, to increase machine utilization, to reduce engineering change orders, and to prevent expensive machine tool crashes. A virtual machining model assists planning the machining process through early simulation of the tool path operations. Once the tool path is verified and optimized, the engineer can validate the entire NC process using a model of the machining center including tool changer and material handling devices.

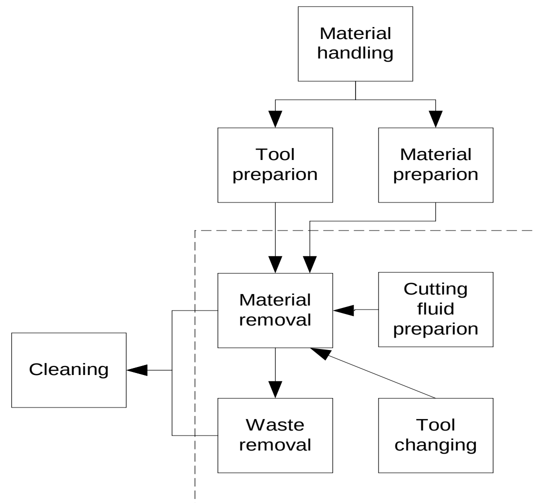

Figure 2. Machining system boundaries diagram

Machining simulation ensures that the process plan and NC program are complete and correct before jobs are released to the shop floor. In turn, it will lower the environmental impact. The concept of virtual machining model has been accepted and machining simulations have been used previously. But the analysis of sustainable machining effects is neither widely understood nor implemented.

A virtual machining model developed using the proposed methodology may include functions for analyzing the environmental impact such as energy consumption, emissions, material mass loss, cutting fluid waste, lubricant oil waste and cutting tool usage. The data generated by the virtual machining model, combined with reference data, tool data and material data, can be used to determine the sustainability parameters. From the modeling and analysis of this information, the simulation system, i.e., the virtual machining model, can evaluate different machining strategies for environmental impact. Figure 3 shows the virtual machining model using the proposed methodology and its inputs and outputs. In order to perform sustainability analysis, provide valid analysis, the virtual machining model should be a validated model, i.e., both the mechanical components and the control of the model need to be correctly reflect the real machine. It is important to have clear goals to achieve sustainable machining. Several general objectives of sustainable machining are listed in [17]:

- Reduce machining process energy consumption
- Minimize waste (generate less waste and increase waste reuse or recycling)
- Use resources efficiently
- Use recyclable materials or reuse machine-tool components

- Improve the management of metalworking fluids, swarf, lubricant oils, and hydraulic oils (improve environmental, health, and safety performance)
- Adopt life cycle assessment methods

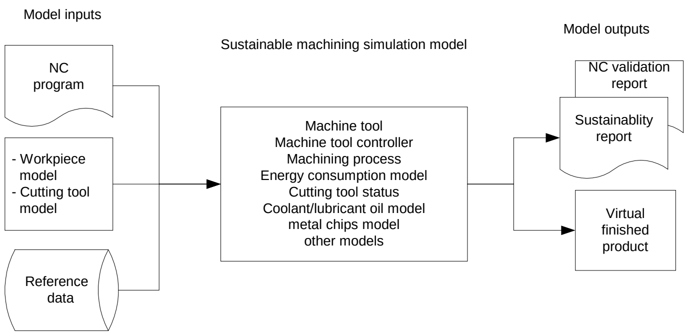

Figure 3. Proposed virtual machining model with environmental impacts analysis

The proposed methodology will help to achieve these objectives. The virtual machining model can be implemented in:

- STEP-NC, which connects the Computer Aided Design (CAD) data used to determine the machining requirements for an operation with the Computer Aided Manufacturing (CAM) process data that solves those requirements [18].
- Delmia Virtual NC
- Siemens NX simulation

The virtual machining model provides an open environment in which user-defined process algorithms can be evaluated, refined, and implemented. The following sustainability machining elements need to be developed:

- Energy consumption model include servo and spindle motors as well as peripheral devices such as coolant pump, compressor, and standby
- Emission model that can be converted from energy consumption
- Material mass loss model based on the product and its stock
- Cutting fluid usage model based on the machining time and fluid LCA data
- Lubricant oil waste model based on machining time and the LCA data
- Cutting tool usage model based on the tool wear due to machining time and cutting conditions and LCA data

These sustainable machining elements need to be integrated into the traditional virtual machining model. Energy consumption may be expressed using mathematical models. The following sections describe the model inputs, sustainability measures and the model output.

Model Inputs

As shown in Figure 3, the inputs to the simulation system are NC programs, virtual models of workpiece and cutting tools, and reference data. These input data may be obtained from LCA database, real world, or virtual world as shown in Figure 1.

NC Program

An NC program contains a set of instructions, i.e., the sequences of machining operations to produce a designed part. It also provides instructions for starting and stopping the peripheral devices using miscellaneous functions – M codes. For example, information about coolant on, coolant off, and spindle on can be derived from the NC statements.

It is the basic input to the virtual machining model and can be validated using the model. An optimized NC program may have shorter machining time to produce the part, therefore, the energy consumption, tool usage, coolant and lubricant usage are all lowered, and the total emission will be lowered also. NC programs for different parts provide different scenarios and results of environmental impact. In addition, different NC programs for the same part can be used to evaluate the difference of environmental impact.

Virtual Models of Workpiece and Cutting Tools

In order to execute the NC program on the virtual machining model, virtual models of workpiece and cutting tools have to be developed based on the features, shape and size of the part design and stored in the workpiece and toolset database. The workpiece size and geometry play an important role in deciding the amount of waste generated, time required, and energy consumed.

Reference Data

Reference data is any necessary data other than what can be provided by the simulation, for the determination of the environmental impact. It includes machine specification data, LCA data, cutting speed tables, feed rate tables, specific energy tables, tool tables, spindle power specification, provided in the machine tool reference manual, and other real world data. Since the data is raw data, sometimes, it needs to be converted and computed to derive the data of interest.

Real world data is the data collected from the machine systems in the shop floor. Real world data could be collected directly from devices or come from databases or other IT-systems. For example, sustainable data from a real machine may be extracted by the following systems:

- MTConnect: MTConnect is a standard for accessing data directly from Computer Numerical Controlled (CNC) machines [19]. It is a middleware standard that provides the capability of extracting data from machine tools during operation to other systems for further processing using the eXtensible Markup Language (XML) standard. MTConect provides the mechanism for process and system monitoring and optimization with respect to energy and resources. The information on the efficient use of machines and systems in the production facility (including use of consumables such as water, fluids, etc) will be valuable to designers of tools, processes and systems to achieve the goal for greener manufacturing systems and facilities.

- The Object Linking and Embedding for Process Control (OPC): OPC is an existing technique for monitoring manufacturing systems and their status [20]. The OPC standards specify the communication of industrial process data, alarms and events, historical data, and batch process data between sensors, instruments, controllers, software systems, and notification devices.

The real world data from the machine using the above methods consist of:

- Cycle time
- Setup time
- Changeover time
- Mean Time Between Failure
- Mean Time To Repair
- Feed rate
- Speed
- Acceleration
- Volumetric rate
- Energy consumption
- The material requirements for each process step

Sustainable Machining Simulation Model

Once simulation system objective, scope, model elements, and its input/output requirements are defined, Input/output transformation will be the major modeling work, it is the mechanism to realize the relationships among the inputs and outputs. Logic, coding of certain algorithms, calculation, and visualization are all part of it.

In addition to the functionalities of a traditional virtual machining model, i.e., the machine tool model, the controller model, etc., the sustainable machining simulation model developed using the proposed methodology is planned to evaluate machining strategies. The following are the measures of sustainability associated with machining operations:

- Energy consumption, direct and indirect
- Carbon emissions, direct and indirect
- Air pollutant emissions (NOx, Volatile Organic Compound)
- Toxic material used (cutting fluids and coolant)
- Liquid waste
- Cutting tool usage status
- Solid waste (chips generated during machining)
- Hazardous waste

Algorithms such as those developed by Narita and Fujimoto [3] can be used to model the environment impacts for machining system. For example, the algorithms to calculate the equivalent CO_2 emission of the sustainability impacts for cutting tool and metal chips are listed below:

Cutting tools are managed based on the tool life, which is compared to machining time to calculate the sustainability impact in one machining.

$$Te = MT / \sum_{j=1}^{RN+1} TLj \times ((TPe+TDe) \times TW + RN \times RGe) \quad (1)$$

Where Te: Sustainability impact of cutting tool in carbon dioxide equivalents (kg-GAS)
MT: Machining time (s)
TL: Tool life (s)
TPe: Sustainability impact of cutting tool production (kg-GAS/kg)
TDe: Sustainability impact of cutting tool disposal (kg-GAS/kg)
TW: Tool weight (kg)
RN: Total number of recoveries
RGe: Sustainability impact due to recovery (kg-GAS)

Metal chip recycling generates sustainability impact that can be calculated based on chip weight as follows:

$$CHe = (WPV-PV) \times MD \times WDe \quad (2)$$

Where CHe: Sustainability impact of metal chips in carbon dioxide equivalents (kg-GAS)
WPV: Workpiece volume (cm^3)
PV: Product volume (cm^3)
MD: Workpiece material density (kg/ cm^3)
WDe: Sustainability impact of metal chip processing (kg-GAS/kg)

Energy Consumption:

By minimizing the energy usage, not only to lower the operating cost, but more importantly, the environment impact from energy generation (equivalent to carbon dioxide emissions) is reduced, since most energy is generated by burning fossil fuels. Figure 4, adopted from [21], shows the distribution of the energy consumption of different components of a machining process.

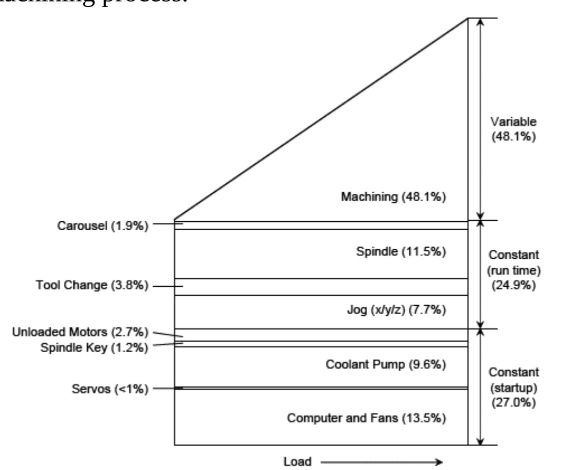

Figure 4. Energy consumption of a machining system (adopted from [21])

The proposed methodology provides an approach that evaluates energy consumption of machining system systematically, energy consumed by all the following elements of the machining system need to be taken into consideration:

- Servomotor
- Spindle motor
- Compressor
- Coolant pump

- Chip conveyor
- Tool changer
- Tool magazine motor
- Control system
- Machine tool idle energy

Emissions:

For machining process, the following four emission indicators have been listed in [9]:

- Global warming potential (g equivalent CO_2)
- Acidification potential (g equivalent SO_2)
- Eutrophication potential (g equivalent PO_4)
- Photo-chemical oxidant formation potential (g equivalent ethylene)

Coolant/Lubricant Fluids:

Oil-based Coolant/Lubricant fluids are one of the most unsustainable elements of machining processes. Cutting fluids, with serious health and environmental issues stemming from their use and disposal, are often studied as an area for potential improvement [17]. The analysis of these impacts will help people have a better understanding and make wise decision.

Cutting Tool Usage:

Cutting tools are managed based on tool life, which is the time for a newly sharpened tool that cuts satisfactorily before it has to be removed for regrinding or replacement. The wearing of tools contributes significantly to the waste in the form of worn particles and a used worn tool at the end of its useful life is of importance as they are often disposed off and hence is a burden to the environment. A worn tool can be identified by the process performance in terms of the cutting forces, energy consumed, and surface finish. Study of the cutting tool usage that includes cutting condition and cutting speed will help to lower its environmental impact and cost.

Material Mass Loss:

Machining process produces waste in form of chips. These chips are mixed with cutting fluids and lubricants, so recycling them requires that they be cleaned, which increases costs. So by comparing the environmental impact from different stock sizes, shapes, and material, an optimal solution of the best combination can be found.

Model Outputs

The simulation will provide output as statistics in a table, chart, and text forms. The statistics are calculated and collected in each single run. By analyzing and comparing outputs from various scenarios, optimized machining strategy can be derived. Companies can analyze sustainability impacts of their processes and determine the improvements without extra investment. This paper is focused on sustainability analysis, but the NC program needs to be validated first, only the sustainability analysis using a validated NC can provide useful results.

NC Validation Report

The NC validation report can include:

- Validated NC programs
- Simulation reports
- Warning messages
- Error messages

The simulation report from virtual machine will consist of:

- Cycle time
- Feed rate
- Speed
- Acceleration
- Volumetric rate
- Tool utilization
- Depth of cut

Sustainability Report

A sustainability report will be a summary of the environmental impact of different measures listed in the previous section. The simulation results of different scenarios can be analyzed by comparing with a baseline model. Conclusion and suggestions can be provided to the factory floor for improvement based on the sustainability analysis.

Virtual Finished Part

The finished virtual product is obtained by executing the NC program in the virtual world. It can be used compare to the design part to validate the accuracy of the virtual machining model. It can also be used for input to another model or system.

CASE STUDY TO TEST THE PROPOSED METHODOLOGY

In order to test the proposed methodology, a case study is defined and procedures are provided to implement it.

Case Study Setting

This case study is for milling operations of a machining center. The case study is used to 1) test the data collection method for sustainability information, 2) implement the simulation modeling of sustainability indicators for machining, 3) validate and optimize the NC program, 4) evaluate the sustainability impacts, 5) provide analysis of the simulation results, 6) generate analysis reports. A brief introduction of possible scenarios and required data are given in the following sections.

In our previous work, a virtual machining model of MAKINO A55 has been developed to execute NC programs and to validate the NC programs using Delmia Virtual NC [22]. A unique soft NC controller - Mimic configuration file has been created. Figure 5 shows the model. The purpose of this model was to validate and optimize the NC program, test collisions in a virtual world and save real machining time. For sustainability impact analysis, new functionalities need to be incorporated into the existing model. A test part needs to be selected; its NC program needs to be generated. Tools, stock material, coolant and lubricant types need to be specified. Specific LCA data associated with all the elements need to be collected. Data from the machine specification, tool specification and others need also to be collected. Algorithms for calculation of environmental impacts of most important measures that mentioned previously [3] will be used to derive the analysis results, most of the input data will be generated by this virtual environment.

Figure 5. Virtual machining center of MAKINO A55

Collecting Required Information

This section describes how to collect the required information. Table 1 lists the method to retrieve some of the information needed.

Table 1: Description of the required information

Data item	Description
Tool Specifications	The selected cutting tool related information is stored in a tool database. Based on the unique tool Id listed in the NC program, the cutting tool material, tool diameter, tool length, and the number of cutting edges can be obtained from the tool database.
Depth of Cut	The virtual machine continuously provides the depth of cut of each NC statement.
Width of Cut	In a milling operation, the width of cut can be either the difference of two X's or Y's values depending on the machining axis.
Linear Feed Rate	Linear feed rate can be obtained from the NC statement. It is valid for subsequent NC statements until a new value is listed.
Spindle Speed	Spindle speed can be obtained in the same way as the linear feed rate from the NC statement.
Material Removal Rate	The virtual machine provides function to obtain the material removal rate.
Recommended Machining Parameters	Recommended machining parameters such as cutting speed, feed rate per cutting edge, or specific energy can be obtained from reference books. Some of these parameters depend on cutting tool material and workpiece material type.

Computing Required Information

When performing the modeling and calculation of sustainability impacts, there may be information that cannot be retrieved directly from the system or NC statements, for which computations are needed. Also, in order to ensure the recommended values are consistent with the unit of measure given in the NC program, unit conversion/computation is often performed. These conversion/computation processes are parts of data collection and processing as shown in Figure 1. For example, if one wants to have a minimized total emission by changing the cutting condition, there is a need to convert the cutting speed to spindle speed, or vice versa. There are also examples of computing linear feed rate and spindle power [23].

Cutting Speed vs. Spindle Speed

The following equeation is used to convert "recommended cutting speed" V to "spindle speed" S.

$$V = \pi * D * S. \text{ Or } S = V / (\pi * D) \quad (3)$$

Where S is spindle speed (rev/min), V is cutting speed (mm/min or in. /min), and D is cutting tool diameter (mm or in.).

Linear Feed Rate

The following equation is used to compute linear feed rate.

$$F = f * n * S \quad (4)$$

Where: F is linear feed rate (mm/sec or in. /min), f is recommended feed rate per cutting edge (mm/edge or in. /edge), n is number of cutting edge of cutting tool (edge/rev), and S is spindle speed (rev/min).

Spindle Power

Energy consumption of spindle will affect material removal rate. It can be calculated in the virtual environment. Spindle power can be calculated using the formula [24].

$$N_m = MRR * \mu \quad (5)$$

Where N_m is spindle power (W or hp), μ is recommended specific energy ($W*sec/mm^3$ or $hp*min/in.^3$), and MRR is material removal rate (mm^3/sec or $in.^3/sec$). MMR can be obtained either from the simulation or computed by using formula,

$$MRR = w * d * F \quad (6)$$

Where w is width of cut (mm or in.), d is depth of cut (mm or in.), and F is linear feed rate (mm/sec or in. /min).

CONCLUSION

Machining is one of the important material removal processes in manufacturing. Therefore, a study of the environmental impact of a machining system contributes greatly to sustainable manufacturing. This research has proposed a novel methodology, which will provide a virtual environment that allows performing the analysis of sustainability impact of machining operations in a systematic manner. Performing analysis offline in a virtual world could save real machine time. The analysis report can be used to help improvement on machining strategy, scheduling, planning, and configurations. Using this method, a machining simulation model can be developed and executed by using inputs such as NC programs, models of workpiece and tools, and reference data. The simulation results can then be analyzed to aid decision makers by providing a better understanding the sustainability situation through analysis of the environmental impact. And then to have a better decision making regards sustainable machining.

This research will provide a solution for a burning topic – analysis of environmental impact using simulation models for sustainable machining in a shop floor environment. In the future, more detailed reference data will be collected and a database for the simulation results will be developed. A decision guidance system that analyzes the environmental impact data to derive an optimal measure based on the desires from the decision maker will be integrated with the simulation system.

DISCLAIMER

No approval or endorsement of any commercial product by the National Institute of Standards and Technology is intended or implied. Certain commercial software systems are identified in this paper in order to facilitate understanding. Such identification does not imply that these software systems are necessarily the best available for the purpose.

REFERENCES

[1] Department Of Commerce (DOC): sustainable manufacturing initiative and public- private dialogue. Available via <http://www.trade.gov/competitiveness/sustainablemanufacturing/index.asp> [accessed Jan. 15, 2010].

[2] Kuhl, M. and Zhou, X., 2009, "Sustainability Toolkit for Simulation-Based Logistics Decisions," Proc. of the 2009 Winter Simulation Conference, eds. M. Rossetti, R. Hill, B. Johansson, Piscataway, New Jersy: Institute of Electrical and Electronics Engineers, Inc.

[3] Narita, N. and Fujimoto, H., 2009, "Analysis of Environmental Impact Due to Machine Tool Operation," International Journal of Automation Technology, Vol. 3.

[4] Delmia, 1995, "Virtual NC Reference Manual," Delmia, Auburn Hills, MI.

[5] Kibira, D., McLean, C. R., 2008, "Modeling and Simulation for Sustainable Manufacturing". Proc. of the 2nd IASTED 2008 Africa Conference on Modeling and Simulation.

[6] Environmental Protection Agency (EPA), LCA Page, 2010, http://www.epa.gov/nrmrl/lcaccess/.

[7] Dahmus, J. B. and Gutowski, T. G., 2004, "An Environmental Analysis of Machining," Proc. of the 2004 ASME International Mechanical Engineering Congress and RD&D Expo., Anaheim, California.

[8] Kopec, J., 2009, "Achievements of Sustainable Manufacturing by Machining," Journal of Achievements in Materials and Manufacturing Engineering, Volume 34, Issue 2.

[9] Campatelli, G., 2009, "Analysis of the Environmental Impact for a Turning Operation of AISI 1040 Steel," Innovative Production Machines and Systems Conference, 5th Virtual Conference, eds. Zhu, Z. and Mekid S.

[10] Kopec, J. and Pusavec, F., 2009, "Sustainability Spirit in Manufacturing/machining Processes," Proc. of Portland International Center for Management of Engineering and Technology, Portland, Oregon.

[11] Akbari, J., Oyamada, K. and Saito, Y., 2001, "LCA of Machine Tools with Regard to their Secondary Effects on Quality of Machines Parts," Proc. of 2nd International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign'01), December 11-15, 2001, Tokyo, Japan, Institute of Electrical and Electronic Engineers, Inc.

[12] Sheng, P., Bennet, D., Thurwachter, S., and von Turkovich, B.F., 1998, "Environmentally-Based Systems Planning for Machining," CIRP Annals – Manufacturing Technology, pp 409-414, Volume 47, Issue 1, Published by Elsevier B.V.

[13] Dietmair, A. and Verl, A., 2009, "A generic energy consumption model for decision making and energy efficiency optimizsation in manufacturing," International Journal of Sustainable Engineering, Vol. 2, No. 2, 123-133.

[14] Narita, H, Chen, L.Y., Kawamura, H., and Fujimoto, H., 2003, "Evaluation System for Machine Tool Operation under Consideration of the Global Environment," Environmental Informatics Archives, Volume 1, pp 348 - 356, ISEIS Publication.

[15] Narita, H., Kawamura, H., Norihisa, T., Chen, L., Fujimoto, H., and Hasebe, T., 2006, "Development of Prediction System for Environmental Burden for Machine Tool Operation (1st Report, Proposal of Calculation Method for Environmental Burden)," Japan Society of Mechanical Engineers: International Journal, Series C, Vol. 49, No. 4, pp. 1188-1195.

[16] Narita, H., Kawamura, H., Chen, L., Fujimoto, H., Norihisa, T., and Hasebe, T., 2008, "Development of Prediction System for Environmental Burden for Machine Tool Operation (2nd Report, Proposal of Evaluation Indicator for Eco-efficiency)," Journal of Environment and Engineering, Vol. 3, No. 2.

[17] Pusavec, F., Krajnik, P. and Kopac, J., 2009, "Transitioning to sustainable protection – Part I: application on machining technologies," Journal of Clean Production, 1-11.

[18] STEP-NC Resource Page, 2009, <http://www.steptools.com/library/stepnc/>.

[19] Vijayaraghavan, A., Sobel, W., Fox, A., Warndorf, P., Ornfeld, D., 2008, "Improving Machine Tool Interoperability using Standardized Interface Protocols: MTConnect," International Symposium on Flexible Automation.

[20] Object Linking and Embedding for Process Control (OPC) resource page, 2009, http://www.opcfoundation.org.

[21] Kordonowy, D. N., 2002, "A Power Assessment of Machining Tools," Bachelor of Science Thesis in Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.

[22] Shao, G, Lee, Y. T., and McLean, C., 2003, "Manufacturing Data Validation through Simulation," Proc. of the 2003 European *Simulation* and Modeling, *Naples, Italy*, pp. 323-327.

[23] Serope K., 1995, "Manufacturing Engineering and Technology," Addison Wesley Publishing Company.