A Prototype of Modeling and Simulation for Sustainable Machining

Guodong Shao, Deogratias Kibira, Kevin Lyons
Manufacturing System Integration Division
National Institute of Standards and Technology
Gaithersburg, MD 20899-8260, U.S.A.

Eric Chernow
Department of Industrial and Systems Engineering
State University of New York at Binghamton
Binghamton, NY 13902-6000, U.S.A.

Abstract—**Modeling and Simulation (M&S) techniques have frequently been utilized to analyze manufacturing processes. The simulation of Numerically Controlled (NC) machine tools is preferred to real machine testing of the programs due to the potential savings of time and money. By validating these NC programs in a virtual environment, damage to valuable machines and cutting tools can be prevented, and production would not be interrupted in the factory. However, little work has been done in applying modeling and simulation techniques to the analysis of sustainable machining. This paper introduces research work to integrate a traditional virtual NC machining model with sustainability models for environmental impact analysis of machining operations. Aspects of sustainable machining modeled and evaluated include energy consumption, coolant and lubrication usage, and waste management. The technique of Life Cycle Assessment (LCA) was applied for this task. A prototype of a machining simulation model was created. The sustainability impact analysis modules were developed and integrated.**

Keywords*-modeling and simulation; sustainable machining; life cycle assessment; virtual machining model.*

I. INTRODUCTION

The United States Department of Commerce recently identified sustainable manufacturing as one of its high priority performance goals, and defined 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]. The adoption of sustainable development in manufacturing offers industry a cost effective route to improve economic, environmental, and social performance [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, coolant and lubricant usage, chips waste, and energy consumption. Therefore, the analysis of machining systems, input, and output factors has significant implication for sustainable manufacturing. However, as has been observed, the relationship between machining technologies and environmental impact remains insufficiently investigated [3]. Modeling and Simulation (M&S) has been proven to be an effective tool for reducing manufacturing costs, improving quality, and reducing the time to market. A machining simulation model allows visualizing and analyzing the functionality of a Computer Numerical Controlled (CNC) machine tool, the machine's controller, and the material removal process. The output data during the machining cycle are analyzed to optimize the program cycle time, tool life, and surface finish. Using a machining simulation model, all experiments can be performed in a safe environment [4]. Kibira and McLean have described a vision for M&S of sustainable manufacturing [5]. However, little work has been done to incorporate sustainability analysis into simulation models.

Life Cycle Assessment (LCA) method analyzes parameters such as energy, resources, impact and outputs, e.g., electricity, total energy, emissions, and waste. The results from these analyses provide guidance on the relative impacts of different types of products, materials, services, or industries with respect to resource use and emissions throughout the life cycle. The objective of LCA is to quantify the sustainability impacts of a process or a product from cradle to grave [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 introduces a prototype machining model that uses a simulation model of a machining system to analyze the environmental impact of the process. This approach allows assessing the environmental impact in a virtual environment using real world data, specification data, and simulation data as inputs and providing a platform to evaluate different options for optimal decision making. The outputs of this system include the virtual machined part for geometry validation, a NC validation report detailing any collisions between the tools and machine and NC optimization, and the sustainability report outlining the environmental effect of that particular operation. This research project can help the manufacturing industry have a better understanding of the issues surrounding sustainable machining and take actions to reduce their negative environmental impacts accordingly.

This paper is subdivided into five main sections. Section II discusses related work, Section III describes the machining simulation model, validation of the simulation model, and sustainability analysis of the machining system. Then a case

The research work was sponsored by NIST Sustainable and Lifecycle Information-based Manufacturing (SLIM) program and Summer Undergraduate Research Fellowship (SURF) program.

study is described in Section IV. Section V concludes the paper.

II. RELATED WORK

Related to this research, previous research includes development of a geometric simulator, VMSim, to calculate the coordinate systems necessary to identify the collision points and other objects of interest during the simulation process [8]. The authors reported a way to modify the NC program without rerunning it. Both linear and circular interpolations were used to eliminate unnecessary cutting and determine the best cutting route from point to point. This approach significantly reduces the amount of error in a manufacturing process. However, there is no mention of how the reduction of unnecessary movements could impact sustainability.

Narita and Fujimoto [3] have developed algorithms to calculate the environmental burden of machining operations. There are three case studies [9], each of which details the applications and use of the algorithm. In the first, VMSim was used to simulate material removal and the force needed for each of the cutting coefficients. The force was in turn used to calculate the cutting torques required and then the CO_2 emission. The second study detailed a comparison between two different NC programs performing the same action. The tool path pattern and machining strategies could not be compared using traditional methods, but the algorithm determines the better choice for the program. Finally, in the third study the effects of high-speed milling and coolant usage were examined. It was found that although the environmental burden of using the cutting tool was decreased with a coolant, both electricity consumption and CO_2 emission increased. The algorithm was then enhanced to calculate the sustainability factors under a common denominator of kg-GAS.

The basic concept of LCA is mentioned in [10], and the paper argues that a clear understanding of LCA is not possible without exploring the technique of Life Cycle Inventories (LCI).

Reference [11] integrates the ideas of modeling and simulation, the life cycle assessment methods, and sustainable manufacturing. The authors also note that much of the work done previously has yet to be collected into a succinct and sound methodology. They developed a nineteen step procedure for the simulation modeling and analysis of sustainability indicators. The prototypical model described in this paper was developed by following similar steps.

III. MACHINING SIMULATION FOR SUSTAINABLE ANALYSIS

A modeling methodology that includes defining a problem, setting up objectives of the study, selecting software, identifying modeling methods, developing the model, executing the model, and analyzing the simulation results was described in [11].

The following subsections discuss machining simulation modeling, validation, and integration of the model with sustainable analysis.

A. *Machining Simulation Model*

A machining simulation model is an interactive 3D visual and logical representation of machining operations. 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 provides a simulation environment for emulating, validating, and optimizing the NC machine process. It is done off-line, thereby keeping the actual machine tool in production.

B. *Validation of the Machining Simulation Model*

To perform sustainability analysis and provide valid analysis and credible simulation results, the machining simulation model should be validated, i.e., both the mechanical components and the controller of the machining model need to correctly reflect the real machine. Validation and credibility are major concerns of developers and users of simulation models because simulation results have impacts on potential decisions.

Input data of simulation models are also very critical for validity of the simulation model [12]. Figure 1 is the flowchart that shows the validation of the machining simulation model using real world data. The methodology includes real machine and virtual machine output data collection, and data set comparison using statistical methods. To validate the machining simulation model, a working NC program needs to be executed on both a real machine and its simulation model. The outputs of both machines (real and virtual) are compared. The simulation model is then repeatedly updated based on the comparison results until repeated satisfactory results are obtained.

Real machine output data are the data collected from the machine systems on the shop floor. Real data may also come from databases or other IT systems in a company. They can be extracted through the following systems:

- MTConnect: MTConnect is a proposed standard for accessing data directly from Computer Numerical Controlled (CNC) machines [13].

- The Object Linking and Embedding for Process Control (OPC): OPC is an existing technique for monitoring manufacturing systems and their status [14].

The real machine data consist of cycle time, setup time, changeover time, mean time between failures, mean time to repair, feed rate, speed, acceleration, volumetric rate, energy consumption, and the material requirements for each process.

Virtual machine data can be obtained from the virtual machine, i.e., machining simulation model. Virtual machine data consist of cycle time, feed rate, speed, acceleration, volumetric rate, tool utilization, depth of cut, energy consumption.

With a valid machining simulation model, the sustainability impacts from the machining process can be evaluated in a virtual environment. A valid model can provide the decision makers with valuable analysis of the machining process based on the input NC data.

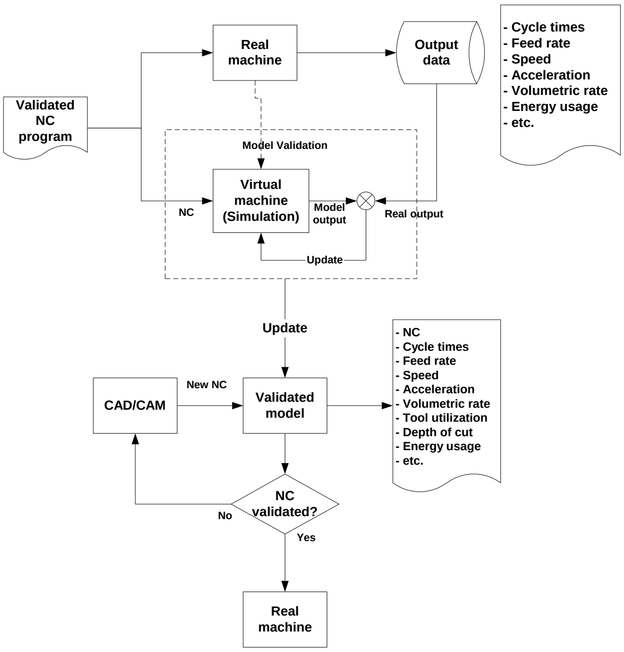


Figure 1. Virtual machine model validation methodology

C. Sustainability Performance Analysis Using Machining Simulation Model

It is important to have clear goals to achieve sustainable machining. Several general objectives of sustainable machining are listed in [2]. They include 1) reducing energy consumption, 2) minimizing generated waste, 3) improving the management of metalworking fluids, swarf, lubricant oils, and hydraulic oils for environmental, health, and safety performance, and 4) adopting life cycle assessment methods.

Based on these general goals, a machining simulation model should 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 machining simulation 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 can evaluate different machining strategies for minimal environmental impact. For this to be effected, the different sustainable machining elements need to be modeled and integrated into the traditional machining simulation model. Figure 2 shows the overview of the sustainable machining simulation model using the proposed methodology and its inputs and outputs. The following sections describe the model inputs, sustainability measures, and the model output.

1) Model inputs

As shown in Figure 2, the inputs to the simulation system are the NC programs, virtual models of workpiece and cutting tools, and reference data.

a) NC programs

An NC program contains a set of instructions that is the sequences of machining operations to produce a designed part. It also provides instructions for starting and stopping the

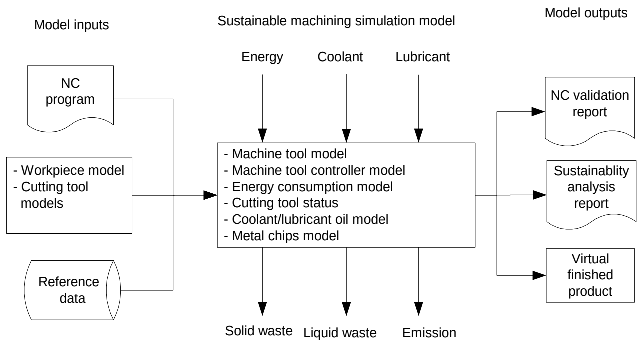


Figure 2: Overview of sustainable machining simulation model

peripheral devices using miscellaneous functions, e.g., coolant on, coolant off, and spindle on. As shown in Figure 1, NC programs are normally generated by Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) systems.

NC program is the basic input to the machining simulation model and can be validated using the model. An optimized NC program has shorter machining time to produce a part. Therefore, the usage of energy, tool, coolant and lubricant, and the total emission are subsequently reduced. Different NC programs for the same part can be used to evaluate the difference in environmental impact.

b) Virtual models of workpiece and cutting tools

To execute the NC program on the model, virtual models of workpiece and cutting tools are 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.

c) Reference data

Reference data are any necessary data other than what can be provided by the simulation model. These data can be obtained from CAD/CAM systems, LCI database, real machines, or other manufacturing systems. It includes machine specification data, cutting speed tables, feed rate tables, specific energy tables, tool tables, spindle power specification, and machine tool reference manual data. Since the data are raw data, it often needs to be converted and computed to extract the useful information.

Once the sources that contain meaningful sustainability data have been identified, data can be collected. The data need to be processed so that only a useful subset of the raw data can be used. The process includes editing, formatting, adding, and removing, according to the description in [15].

2) Sustainable machining simulation model

The sustainable machining simulation model is developed to evaluate machining strategies. Algorithms such as those developed by Narita and Fujimoto [3] can be used to model the environmental impacts of a machining system. Five factors were considered to compute the total environmental impact of the machining process. These factors are electric consumptions of the machine tool (Ee), coolant quantity (Ce), lubricant oil quantity (LOe), metal chip quantity (CHe), and cutting tool status (Te). There are a total of forty-two variables identified in all the algorithms. For the variables that depend on the machine tool, the LCI database can be used to refer to some of the values needed. In addition, values can be cited from environmental reports, technical reports, and company database. As examples, the algorithms to calculate the equivalent CO_2 emission of the sustainability impacts for lubricant oil and metal chips are listed below:

Lubricant oil is mainly used for spindles and slideways. The amounts of oil-air lubricant supplied by a pump to spindles within a specific interval are considered. The sustainability impact due to lubricant oil is calculated as follows:

$$LOe = SRT/SI \times SV \times (SPe+Sde) + LUT/LI \times LV \times (LPe+LDe) \quad (1)$$

Where SRT: NC program spindle runtime (s)
SV: Spindle lubricant oil discharge rate (L)
SI: Mean interval between discharges (s)
SPe: Sustainability impact of spindle lubricant oil production (kg-GAS/L)
SDe: Sustainability impact of spindle lubricant oil disposal (kg-GAS/L)
LUT: NC program slideway runtime (s)
LI: Mean interval between supplies (s)
LV: Lubricant oil quantity supplied to slideway (L)
LPe: Sustainability impact of slideway lubricant oil production (kg-GAS/L)
LDe: Sustainability impact of slideway lubricant oil disposal (kg-GAS/L)
(Grease as a lubricant is not treated here, but the same equations can be adapted to calculate the sustainability impact for grease.)

Metal chip recycling has a 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)

a) Energy consumption

To provide a systematic evaluation of total energy consumption of the machining operation, the following elements of the machining system need to be considered: 1) servomotor, 2) spindle motor, 3) compressor, 4) coolant pump, 5) chip conveyor, 6) tool changer, 7) tool magazine motor, 8) control system, and 9) machine tool idle energy

b) Emissions

The environmental impacts analysis study includes 1) global warming potential (g equivalent CO_2), 2) acidification potential (g equivalent SO_2), 3) eutrophication potential (g equivalent PO_4), 4) human toxicity, and 5) ecotoxicity.

c) Coolant/lubricant fluids

Oil-based Coolant/Lubricant fluids are one of the most polluting elements of machining processes. Cutting fluids, with serious health and environmental issues stemming from their use and disposal, are often investigated as an area for potential improvement [2].

d) Cutting tool usage

Cutting tools are managed based on tool life that is, the time it takes for a newly sharpened tool that cuts satisfactorily to wear out and be removed for regrinding or replacement. The wearing of tools contributes significantly to waste in the form of worn particles and a used tool at the end of its useful life due to its disposal. A worn tool can be identified by the process performance in terms of the cutting time, cutting forces, energy consumed, and surface finish. The study of cutting tool usage that includes cutting condition and cutting speed will help lower its environmental impact and cost.

e) Material waste

Machining processes produce waste in the form of chips. These chips are mixed with cutting fluids and lubricants and recycling them requires that they be cleaned, which increases costs. The best combination of stock size, shape, and material for a part can be obtained by comparison for minimal environmental impact.

3) Model outputs

The machining simulation provides a 3D material removal animation and output statistics in a table, chart, and text forms. The statistics are calculated and collected after execution of the simulation model. By analyzing and comparing outputs from various scenarios, optimized machining strategy can be obtained.

a) NC validation report

This paper is focused on environmental impacts analysis, but the NC program needs to first be validated. The NC validation report can include: 1) validated NC programs, 2) simulation reports, 3) warning messages, and 4) error messages.

b) Sustainability report

A sustainability report is 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.

c) Virtual finished part

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

IV. PROTOTYPE OF MACHINING SIMULATION FOR SUSTAINABLE ANALYSIS

A prototype of a machining simulation model for sustainable analysis has been developed at the National Institute of Standards and Technology (NIST). The prototype model is for milling operations of a machining center. It is used to 1) evaluate the modeling methodology in [11], 2) identify and experiment the collection methods of environmental information, 3) develop a simulation model and environmental factor models for machining, 4) investigate integration options, 5) validate and optimize the NC program, 6) provide analysis of the simulation results, 7) evaluate the sustainability impacts, and 8) generate analysis reports. A brief introduction of possible scenarios and required data are given in the following sections.

In previous work of NIST researchers [16], a machining simulation model of a MAKINO A55 machining center was developed using the Delmia Virtual NC, to validate the NC programs. A unique soft NC controller - Mimic configuration program has been developed. For environmental impact analysis, new functionalities need to be incorporated into the existing model. Figure 3 shows the new machining model developed using Delmia V6 software. The environmental analysis model was developed by implementing the algorithms discussed in section III. Currently, the simulation software does not have the features to perform the sustainability analysis; therefore, models for sustainable manufacturing have to be built using external programs that can be integrated with the simulation model. In this prototype model, Microsoft Excel has been used for environmental impacts calculations and comparison.

A. Prototype Model Inputs

The NC program of the test part was generated. Tools, stock material, coolant types, and lubricant types were specified. Specific LCI data associated with all the elements were collected. Data from the machine specification, tool specification and other data were determined. Algorithms for calculation of environmental impacts of important measures mentioned previous section were used to obtain the analysis results. Most of the input data were generated in this virtual environment. Delmia V6 enables the execution of NC programs by use of a controller emulator.

A Microsoft Excel spreadsheet was created detailing the variables needed to model each of the required environmental factors. As an example, the lubricant oil data are shown in Figure 4. This spreadsheet shows the source of each of the required variables identified as one of three possible choices: 1) simulation output data from the model, 2) reference data that are specific for each machine, or 3) the LCI database. Both the values needed for the LCI database and reference locations were obtained from [3]. In addition, this module was incorporated with the DELMIA machining simulation so that the model sourced variables were able to be provided.

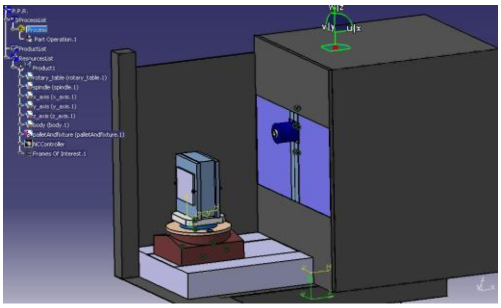


Figure 3: Machining simulation model of MAKINO A55

					Global Warming	Acidification
Environmental Burden	**Variable**	**Definition**	**Units**	**Source**	**CO_2 Value**	**SO_2 Value**
LOe	SRT	NC program spindle runtime	s	Model		
Lubricant Oil	SV	Spindle lubricant oil discharge rate	L	Reference	0.00003	0.00003
	SI	Mean interval between discharges	s	Reference	480	480
	SPe	Enviromental burden of spindle lubricant oil production	kg-GAS/L	Database	0.469	0.00105
	SDe	Enviromental burden of spindle lubricant oil disposal	kg-GAS/L	Database	2.612	0.06466
	LUT	NC program slideway runtime	s	Model		
	LI	Mean interval between supplies	s	Reference	1.8	1.8
	LV	Lubricant oil quantity supplied to slideway	L	Reference	0.228	0.228
	LPe	Enviromental burden of slideway lubricant oil production	kg-GAS/L	Database	0.469	0.00105
	LDe	Enviromental burden of slideway lubricant oil disposal	kg-GAS/L	Database	2.612	0.06466

Figure 4: Sustainability input data

B. Model Integration

After investigating different options, Microsoft Integrator was selected to be the integration mechanism. Microsoft Integrator enables the integration of Microsoft Excel with Dassault Systèmes applications [17]. It allows exporting a table with the chosen parameters from the machining model into Microsoft Excel. With this approach, it is possible to define the required parameters and then output them from the simulation into Excel. In addition, all of the environmental impact calculations using the algorithms are in Excel. The output would be used and displayed in the modeling software. This would fully complete the integration. One advantage to using this system is that changes made on the spreadsheet can be reflected in the output graphs in real time. There would be no need to re-execute the simulation model, but only update the values in Delmia V6 and calculations and display the new results and graphs. Figure 5 shows the model integration overview.

C. Model Output Analysis

Figure 2 shows that there should be three outputs from this process. The first is the NC validation report to confirm that there are no tool clashes or damage to the machine during the execution of the NC program, it includes the optimization of the NC program. If any errors are found, it is the responsibility of the engineer to review the NC program. Since traditional machining would have caused damage to the part, machine, or tool, this is one of the major advantages of using modeling and simulation to test NC programs.

Even without any collision between the tool and machine, the program could still be incorrect if, after inspection and comparison, the finished virtual part is not the same as the design part. An example of a virtual finished product is shown in Figure 6.

Another output of the model would be the sustainability analysis report. This information would be in the form of table, charts and graphs and could be displayed inside of the DELMIA V6 software. Since there were six different environmental burdens, calculations were done for each and the output showing the amount of kg-GAS released displayed. In addition, a pie chart was generated showing the percentage of the total burden arising from each of the effects. An example of the output for global warming is shown in Figure 7.

Figure 5: Model integration

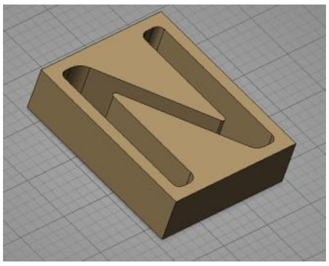
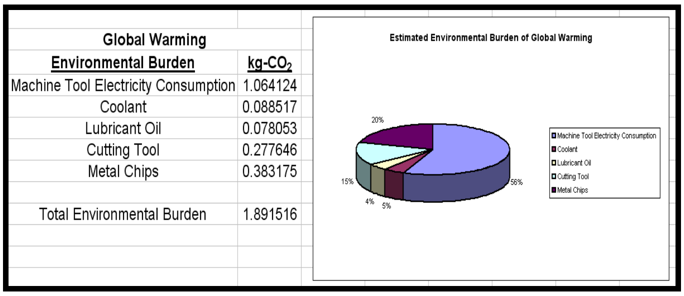


Figure 6: Virtual finished product



Global Warming	
Environmental Burden	$kg\text{-}CO_2$
Machine Tool Electricity Consumption	1.064124
Coolant	0.088517
Lubricant Oil	0.078053
Cutting Tool	0.277646
Metal Chips	0.383175
Total Environmental Burden	1.891516

Figure 7: Sustainability analysis report

V. 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. The research of this paper has proposed a novel methodology, which will provide a virtual environment to allow the analysis of sustainability impact of machining operations. The analysis report can be used to improve machining strategy, scheduling, planning, and configurations. A machining simulation model in DELMIA V6 has been created, and systems for sustainability impacts analysis have been developed and integrated with the software. By using Microsoft Integrator, the models developed in Excel can be fully integrated with DELMIA V6. This has been demonstrated with an example of a machining center model. Such obtained simulation results can be analyzed to aid decision makers by providing a better understanding of the sustainability situation through analysis of the environmental impact. It is hoped that this research project can help the manufacturing industry have a better understanding of the issues affecting sustainable machining and, in turn, companies can make informed decisions to reduce their negative environmental impacts.

Disclaimer

Certain commercial software systems are identified in this paper to facilitate understanding. No approval or endorsement of any commercial product by the National Institute of Standards and Technology is intended or implied. And neither does the identification 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>.

[2] Pusavec, P. Krajnik and J. Kopac, "Transitioning to Sustainable Production – Part I: Application on Machining Technologies," *Journal of Cleaner Production*, August 2009.

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

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

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

[6] ISO 14040: Environmental management – Life cycle assessment – Principles and framework, International Organization for Standardisation (ISO), 2006.

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

[8] H. Narita, L. Chen, and H. Fujimoto, K. Shirase, and E. Arai, "Trial-less Machining Using Virtual Machining Simulator for Ball End Mill Operation," Proposal of Calculation Method for Environmental Burden)," Japan Society of Mechanical Engineers: International Journal, Series C, Volume 49, Number 1, pp. 50-55. 2006

[9] H. Narita, H. Kawamura, L. Chen, H. Fujimoto, T. Norihisa, and T. Hasebe, "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, Volume 3, Number 2. 2008

[10] J. J. Lee, P. O'Callaghan, and D. Allen, "Critical Review of Life Cycle Analysis and Assessment Techniques and their Application to Commercial Activities," Resources, Conservation, and Recycling, Volume 13. 1995.

[11] G. Shao, D. Kibira, and K. Lyons, "A Virtual Machining Model for Sustainability Analysis," Proceedings of ASME 2010 International Design Engineering Technical Conference & Computers and Information in Engineering Conference.

[12] G. Shao, A. Brodsky, P. Ammann, and C. McLean, "Pa-rameter Validation using Constraint Optimization for Model-ing and Simulation," *Industrial Simulation Conference 2009, Loughborough, UK*, June 2009, pp. 323-327.

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

[14] Object Linking and Embedding for Process Control (OPC) resource page, http://www.opcfoundation.org. [accessed Dec. 3, 2010].

[15] A. Skoog, Methods for Input Data Management – Reducing the Time-Consumption in Discrete Event Simulation. Licen-tiate Thesis, ISSN 1652-9243, Department of Product and Production Development, Chalmers University of Technol-ogy, Gothenburg, Sweden. 2009.

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

[17] Microsoft. "Understanding Microsoft Integration Technologies," http://technet.microsoft.com/en-us/library/dd879265%28BTS.10%29.asp [accessed Dec. 3, 2010