Re-engineering Manufacturing for Sustainability

Andrew Y.C. Nee, Bin Song, and Soh-Khim Ong (Eds.)

Re-engineering Manufacturing for Sustainability

Proceedings of the 20th CIRP International Conference on Life Cycle Engineering, Singapore 17–19 April, 2013

Editors
Prof. Andrew Y.C. Nee
Mechanical Engineering
National University of Singapore
Singapore

Prof. Soh-Khim Ong
Mechanical Engineering
National University of Singapore
Singapore

Dr. Bin Song
Institute of Manufacturing Technology
(SIMTech)
Singapore

ISBN 978-981-4451-47-5 ISBN 978-981-4451-48-2 (eBook)
DOI 10.1007/978-981-4451-48-2
Springer Singapore Heidelberg New York Dordrecht London

Library of Congress Control Number: 2013933984

© Springer Science+Business Media Singapore 2013
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

For two decades, the CIRP Life Cycle Engineering (LCE) Conference has continued its steady course since its creation. It has grown significantly beyond its original scopes and objectives and has seen researchers in this field doubled and tripled in the last 10 years. Sustainable manufacturing is a major initiative of almost all the manufacturing industries worldwide, in an effort to prolong the life of products, reduce the use of toxic materials and carbon footprint, conserve energy, not only for meeting the needs of the manufacturers and consumers, but also the multi-stakeholders in the entire business chain.

In 2013, Singapore has the honor of hosting the 20^{th} CIRP LCE, with its organizers from SIMTech , the Singapore Institute of Manufacturing Technology and the National University of Singapore. For Singapore, this is a major CIRP event since the General Assembly which was held in 1994.

The conference has accepted some 117 papers from 28 countries. All the papers have been subject to the rigorous peer review and revision process by experts in the field. The topics covered in LCE2013 include Sustainabledesign – approaches and methodologies, methods and tools; Methods and tools for resource efficient manufacturing; technologies for energy efficient machine tools; Sustainable manufacturing process – machining, cleaning, coating, forming and molding; Analysis and tools for reuse and recycling; Supply chain management; Sustainability analysis – methodologies and tools, various case studies; Sustainability management; Remanufacturing – business and management, design and analysis, process technologies, reliability assessment; Social sustainability.

Keynote speeches will be delivered by eminent researchers in the field of LCE: Prof ShahinRahimifard from Loughborough University, Prof Nabil Nasr from Rochester Institute of Technology, Prof I S Jawahir from University of Kentucky, Prof Zhang Hong-Chao from Texas Tech University.

We would like to thank all the reviewers, authors, support from the National University of Singapore and SIMTech, and all the participants for making LCE2013 a real success. We understand that some participants travel no less than some 15 hours to come to Singapore, and it could also be their very first visit. We wish them a most pleasant stay, and enjoy the food, culture, and the latest attractions in Singapore, in addition to fruitful discussion at the Conference.

Andrew Y.C. Nee, NUS
Bin Song, SIMTech
Soh-Khim Ong, NUS
2013

Organization

Committees

Prof. Andrew Y.C. NEE
Dr. Bin SONG

Organizing Committee

Ms Sam CHAN
Dr. Kiah Mok GOH
Dr. Feifei HE
Dr. Hui Mien LEE
Dr. Chee Wai SHI
Dr. Xianting ZENG

International Scientific Committee

Prof. L. Alting
Prof. A. Bernard
Prof. P. Blecha
Prof. H. Bley
Prof. B. Bras
Prof. D. Brissaud
Prof. P. Butala
Prof. S. Butdee
Prof. J. Chen
Prof. W. Dewulf
Prof. D. Dimitrov
Prof. D. Dornfeld
Prof. J. Duflou
Prof. W. ElMaraghy
Prof. K. Feldmann
Prof. P. Gu
Prof. M. Hauschild
Prof. C. Herrmann
Prof. I. Jawahir
Prof. J. Jeswiet
Prof. S. Kara
Prof. F. Kimura
Prof. W. Knight
Prof. J. LEE
Prof. T. LIen
Prof. M. Lindahl
Prof. W. ‘ LU
Prof. H. Meier
Prof. L. Morselli
Prof. N. Nasr
Prof. A. Nee
Prof. A. Ometto
Prof. S. Ong
Prof. R. Prakash
Prof. S. Rahimifard
Prof. K. Sangwan
Prof. M. Santochi
Prof. G. Seliger
Prof. M. Shpitalni
Prof. W. Sihn
Prof. S. Suh
Prof. E. Sundin
Prof. J. Sutherland
Prof. S. Takata
Prof. C. Tan
Prof. S. Tichkiewitch
Prof. T. Tomiyama
Prof. M. Tseng
Prof. K. Ueda
Prof. Y. Umeda
Prof. H. Brussel
Prof. E. Westkaemper
Prof. H. Zhang

Table of Contents

Keynote

Sustainable Design - Approaches and Methodologies

Sustainable Design - Methods and Tools

Methods and Tools for Resource Efficient Manufacturing

Technologies for Energy Efficient Machine Tools

Sustainable Manufacturing Processes - Machining

Sustainable Manufacturing Processes - Cleaning, Coating, Forming, Molding

Supply Chain Management

Analysis and Tools for Reuse and Recycling

Sustainability Analysis - Approaches and Methodologies

Sustainability Analysis - Methods and Tools

Sustainability Analysis - Case Studies

Sustainability Management

Remanufacturing - Business and Management

Remanufacturing - Process Technologies

Remanufacturing - Design and Analysis

Remanufacturing - Reliability Assessment

Social Sustainability

Erratum

Impact of Machine Tools on the Direct Energy and Associated Carbon Emissions for a Standardized NC Toolpath

Vincent Aizebeoje Balogun[1], Ampara Aramcharoen[2], Paul Tarisai Mativenga[1], and Shaw Kah Chuan[2]

[1] The University of Manchester, Manchester M13 9PL, United Kingdom

[2] Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, Singapore 638075

Abstract

In mechanical machining, significant energy use can be linked to carbon emissions and an increase in manufacturing cost. When machining a given component, the basic energy state dominates the total energy footprint as compared to tool-tip energy. Thus, the choice of machine tool is an important consideration in reducing the energy demand per product machined. In this work, a standardized NC toolpath was milled on machine tools in Singapore and the UK. The work significantly contributes to the knowledge on energy intensity in machining and the associated carbon dioxide emissions by presenting the impact of machine tools and geographical location.

Keywords:

Cutting; Energy footprint; Carbon dioxide footprint; Global manufacturing

1 INTRODUCTION

There is a growing need to quantify the energy footprint in manufacturing processes in order to develop: strategies for reducing energy intensity of products, manage the sensitivity of products due to increase in electricity prices and reduce carbon dioxide footprints. It is now well established that the total direct energy demand during a machining operation is dominated by the electrical energy requirements of the machine tool features [1-8]. This is referred to as the 'fixed' energy [2, 3] or the 'basic' state of a manufacturing resource or machine. The basic energy consumption is influenced by the design of the machine tool [9], and represents the energy demanded by the machine tool when operated at zero cutting load. In recent work, Branker and Jeswiet [10, 11], analyzed the environmental burden involved in the manufacturing of a sprocket on a Bridgeport GX480 VMC. They reported that the auxiliary units of the machine tool system dominated the energy budget.

To reduce the environmental burden (global warming potential) due to energy consumption in mechanical machining processes, energy demand must be reduced in any of the four LCA stages: manufacturing, transportation, use and end of life [12]. Narita et al. investigated the environmental burden for NC machine tools and reported that electricity consumption of the machine tool is the main critical factor from the viewpoint of global warming [13]. For a given component the link between the energy footprint and the carbon dioxide apportioned to the component due to energy use, can be established through the carbon emission signature (CES) [14]. The carbon emission signature is significantly affected by the proportion of carbon rich fuels used in power generation, compared to the percentage of low and carbon neutral power generation sources. The 2010, carbon emission signature, CES for France, Canada, United Kingdom, Germany, Singapore, USA, China and Australia was 0.079, 0.186, 0.457, 0.461, 0.499, 0.522, 0.766, 0.841 kgCO$_2$/kWhr respectively [15].

For 2011, the source of electricity for the UK and Singapore (SG) was as shown in Table 1. From Table 1, it is clear that in Singapore in 2011, the use of natural gas was dominant for power generation stations. Based on the data in Table 1 and Table 2, the CES for the UK and Singapore in 2011 was calculated to be 0.443 kg/kWhr and 0.601 kg/kWhr respectively.

Energy source	**UK (%)** [16]	**SG (%)** [17]
Coal	29.2	-
Natural Gas	40.7	75.8
Nuclear	19.1	-
Renewable	9.2	2.3
Fuel oil	-	21.6
Diesel oil	-	0.3
Other	1.8	-

Table 1: UK and Singapore fuel mix (for comparison).

		1 GJ of heat produced releases	
Type of fuel		**Δ*H* (kJ)**	**CO$_2$ (kg)**
Coal	$C + O_2 \Rightarrow CO_2$	- 394	112
Heavy oil	$C_{20}H_{42} + 30O_2 \Rightarrow 20CO_2 + 21H_2O$	-13300	66
Natural gas	$CH_4 + 2O_2 \Rightarrow CO_2 + 2H_2O$	-890	49
Biomass	$CH_2O + O_2 \Rightarrow CO_2 + H_2O$	-440	100
ΔH = Enthalpy: heat content; thermodynamic potential			

Table 2: Energy production fuels, the heat and CO$_2$ released [14].

1.1 Energy Modelling in Machining

Gutowski et al. [2], based on the analysis of an automobile machining line, proposed a mathematical model for the electrical energy requirement for manufacturing processes as shown in Equation 1.

$$E = (P_0 + k\dot{v})t \tag{1}$$

Where, *E* is the direct electrical energy in (J or Ws) required in machining processes, P_0 is the power consumption in (W), *k* is the specific energy requirement of the workpiece material in (Ws/mm^3), $\dot{v}$ is the material removal rate in (mm^3/s), while *t* is the cutting time in (s).

The need for an appropriate and generic energy estimation model motivated researchers into further work and subsequent models were developed by Diaz et al. [5], Mori et al. [18] and He et al. [19].

A unified and consolidated process planning centric model for machining processes was developed by Balogun and Mativenga [20] as shown in Equation 2. This model considers the effect of machine modules, auxiliary functions, axis movement and spindle speed characteristics for the total electrical energy estimation in mechanical machining processes.

$$E_{total} = E_b + E_r + P_{tc}t_{tc}\left[INT\left(\frac{t_2}{T}\right)+1\right] + P_{air}t_{air} + \left(mN + C + P_{cool} + k\dot{v}\right)t_c \qquad (2)$$

Where E_b, E_r, are the basic and ready state energy demand of the machine tool in (W), P_{tc}, P_{air}, P_{cool} represent tool change, air cutting and coolant power demand respectively and t_{tc}, t_c, *T* represents tool change time (s), cutting time (s) and Tool life (s) respectively, *mN +C* is the spindle speed characteristics model. Other parameters retain their initial meanings.

The generic recommendations from Equation 2 are that the process planning centric direct energy model for machining should take into account

- The Basic and Cutting States, explicitly.
- Modelling the energy required to take a machine tool from the Basic State to a state where the axis and tool is ready for action and about to cut (Ready State).
- Direct energy requirements for spindles based, spindle design, spindle speed and machine tool power-RPM characteristics.
- The energy for tool change and the number of tool changes required.
- A distinction between energy demand for air cutting moves and the energy during toolpath execution when the tool is engaged in cutting.
- Modelling explicitly the influence of cutting speeds, feed and depth of cut to support process planning.
- Modelling machine tool specific accessories/modules.

1.2 Research Motivation

It is clear from energy monitoring of machining processes that the basic or zero load cutting state dominates the energy requirements in machining. Considering this fact, it is important to understand how choice of machine tool can alter the energy demanded for machining a given component and quantify the impact of making such decisions. Moreover, the carbon emission signature is an additional variable that affects the carbon footprint of a machined product. These combined factors have to be evaluated in assessing future costs of CO$_2$ footprints generated by manufacturing facilities. Such decisions can be vitally relevant and have to be taken now and in the future, accounting for the global mobility of capital and businesses and the increasing presence of companies in different geographical zones. This was the motivation for this work. The study was addressed in a round robin energy evaluation on machine tools undertaken by The University of Manchester, UK and Singapore Institute of Manufacturing Technology (SIMTech), SG.

2 ROUND ROBIN ENERGY ASSESSMENT ON MACHINE TOOLS

Two workpiece materials (AISI 316L stainless steel and AISI 1045 steel of dimensions 100 mm long by 50 mm wide and 20 mm height) were used in the end milling tests. The machine toolpath was standardized and evaluated for two cases covering: (i) conventional and (ii) high speed milling machining. The machine tools used were: a conventional speed Takisawa CNC centre and a high speed milling centre the Mikron HSM 400, both located in Manchester, UK. In Singapore, the cutting tests were done on a Hitachi Seiki VG-45 and Roeder RFM 700 for conventional and high speed milling respectively. The toolpath generated was a surface cleaning operation. The selected toolpath was kept simple in order to minimize the impact of the machine controller in modifying toolpath.

The cutting parameters and environment were kept constant as practically as possible for the two test locations. Table 3 shows details of the cutting tests. Electricity consumption was recorded with the Fluke 435 power meter and ELITEpro SP power meter. The vital energy data for the machine tools is provided in Tables 4 and 5 for the conventional and high speed milling tests respectively. This data is the critical energy demand indicators that should be optimized in order to develop energy efficient machining facilities. From Table 4 it is clear that the basic power required for the Takisawa machine is higher than that for the Hitachi machine, being values of 2.79 and 2.22 kW respectively. For the HSM tests, the basic power required for the Mikron HSM machine was 2.92 kW compared to 2.29 kW for the Roeder machine as shown in Table 5. The basic energy demand was 140, 185, 190 and 210 Whr on the Hitachi, Takisawa, Mikron and Roeder respectively. Comparing this to total energy demand in Tables 4 and 5, the basic energy demand was 75.7%, 78.7%, 69.04% and 71.8% on the Hitachi, Takisawa, Mikron and Roeder respectively. This result further confirms the impact of machine tool design and features on energy demand. Thus the design of next generation low energy demand machines could have a profound impact on reducing the energy footprint in machining.

Machine tool	**Takisawa & Hitachi Seiki VG-45**	**Mikron HSM 400 & Roeder RFM 700**
Tool diameter (mm)	50	8
Workpiece material	AISI 316L stainless steel	AISI 1045 steel
Inserts on tool holder	3	4
Spindle Speed (rpm)	650	32000
Depth of cut (mm)	0.5	0.2
Width of cut (mm)	50	0.2
Feed per tooth (mm/tooth)	0.038	0.1
Table feed in cutting (mm/min)	75	12800
Cutting fluid	Flood	MQL 15 ml/hr

Table 3: Machine tools and cutting parameters.

	Takisawa	Hitachi
Spindle Model	A06B-0652-B	Hitachi Spindle 45/4500rpm Main Motor: 15 hp
Spindle maximum power (kW)	11	11
Controller Model	MDSI	SEICOS MKIII controller
P_{basic} (kW)	2.79	2.22
Energy air cutting from area under graph (Whr)	198.1	159.9
Energy during machining with flood, area under graph (Whr)	234.4	185.4

Table 4: Basic Power Data of Machine Tools in Conventional Machining.

	Mikron	Roeder
Spindle Model	HVC140-SB-10-15/42-3F-HSK-E40	Fisher MFW-1230/42, max. 42,000 rpm
Spindle maximum power (kW)	10	14
Controller Model	Heidenhain TNC 410	PC-based customized controller by Roeders
P_{basic} (kW)	2.92	2.29
Energy air cutting from area under graph (Whr)	265.8	279.1
Energy during machining with MQL, area under graph (Whr)	274.8	292.7

Table 5: Basic Power Data of Machine Tools in High Speed Machining.

Detailed power-time domain profile during the air cutting and machining cycle and hence the direct energy requirements are shown in Figure 1, 2, 3 and 4.

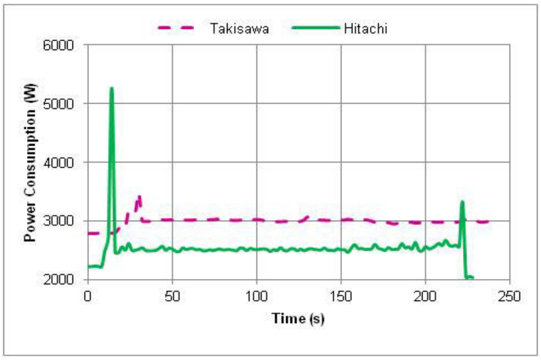

Figure 1: Power profile of Takisawa and Hitachi executing an NC toolpath at 650 rpm and air cutting.

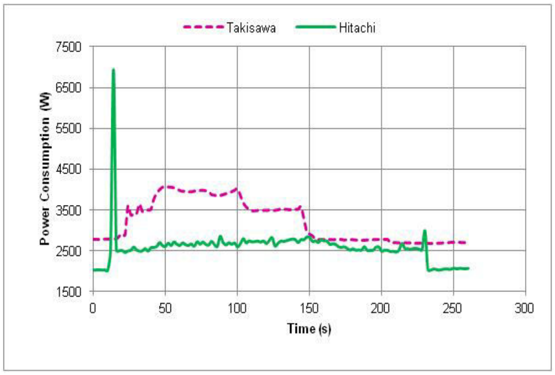

Figure 2: Power profile of Takisawa and Hitachi executing a standardized toolpath at 650 rpm under flood cutting environment machining AISI 316L stainless steel.

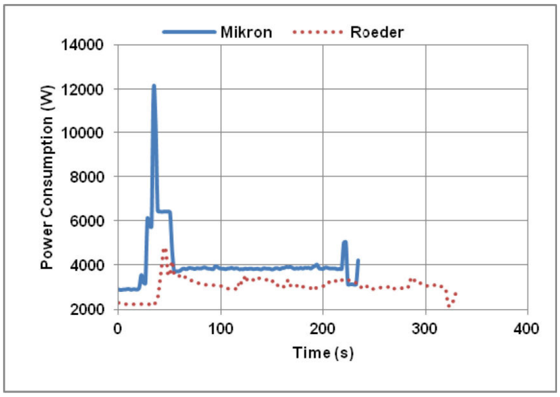

Figure 3: Power profile of Mikron and Roeder operating at zero cutting executing an NC toolpath at 32000 rpm.

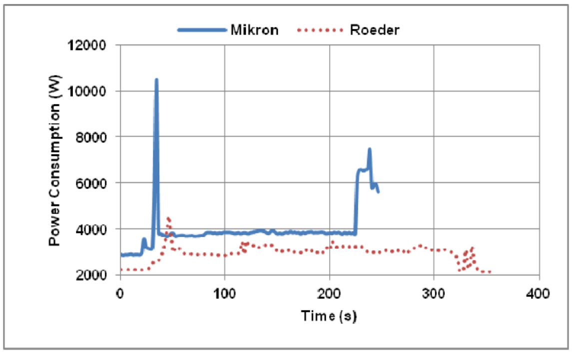

Figure 4: Power profile of Mikron and Roeder executing a standardized toolpath at 32000 rpm under MQL.

As shown in Figures 1, 2, 3 and 4, the power demand of the machine tool spindle causes a high surge in electricity consumption when the spindle is switched on. This is the characteristic peak seen in all the four figures. Comparing Figure 1 to 2, and Figure 3 to 4, it can be seen that the energy demand increases when going from an air cutting pass to actual cutting. Quantitative comparison of the energy state in air cutting compared to that in actual cutting shows that the machine tool energy consumption, which is the energy demand at the 'Basic state' and Ready State [18, 20] (steps that consume energy in preparing the machine for cutting), is 86.7%, 86.3%, 72.6% and 78.1% for Takisawa, Hitachi, Mikron and Roeder milling machines respectively. Testing machining toolpaths in air cutting can have significant contribution to increasing the energy footprint of a machine product or workshop.

3 ENERGY REQUIREMENTS AND CARBON FOOTPRINT IN INTERNATIONAL CONTEXT

Jeswiet and Kara [14], presented a model to evaluate carbon emissions derived from electricity generation as shown in Equation 3. In this equation, the "Carbon Emission Signature" (CES^{TM}) is used to specify CO_2 intensity or emission per unit of energy generated:

$$\text{Carbon emission } [kgCO_2] = EC_{part}\ [GJ] \times CES^{TM}\ [kgCO_2/GJ] \qquad (3)$$

Where EC_{part} is the energy consumed to produce a component or manufactured product and CES^{TM} is the carbon emission signature as calculated for the energy mix. An average carbon intensity factor as specified in Section 1 is used for different geographical locations and countries. In this paper, the electrical energy required for machining each pass was calculated from the area under the power-time domain characteristic graph for the cycle time that the machine was operated.

The energy demand at spindle speed of 650 rpm for machining AISI 316L stainless steel on the Takisawa milling machine, was 20.9% more than machining the same NC toolpath on the Hitachi as shown in Figure 5. These machines were located in the UK and Singapore. However, due to the lower carbon emission signature of 0.443 kg/kWhr for UK, compared with 0.601 kg/kWhr for Singapore, the carbon footprint from direct electrical energy usage when executing the same NC toolpath in Singapore is higher by 7.3% at low speed machining, compared with the UK as shown in Figure 6. Thus the more energy efficient machine can have its environmental impact offset by its geographical location, if it is in a jurisdiction that has a higher carbon emission signature for its electrical energy as delivered from the national grid.

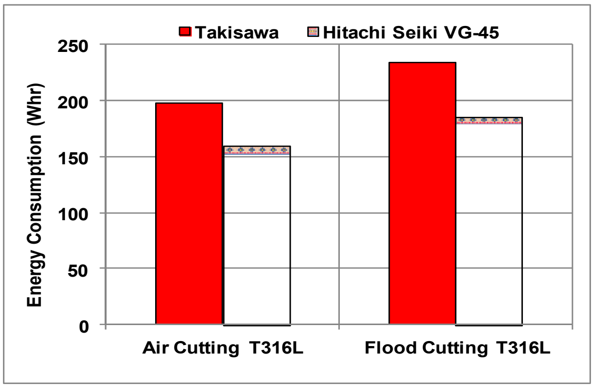

Figure 5: Energy consumption at 650 rpm on T316L.

However, with high speed machining of AISI 1045 steel at spindle speed of 32000 rpm shown in Figure 7, the carbon emission is 44.5% more in Singapore as shown in Figure 8. It can therefore be argued that the machine tool located in Singapore would need to be significantly more energy efficient than that in the UK so that it is not associated with a higher carbon footprint and global warming environmental potential. It appears from the analysis here that the typical differences in the energy demand by different machine tools can be less significant compared to the impact of moving a machine from a region of higher electricity carbon emission signature (CES^{TM}) to a region of lower CES^{TM}.

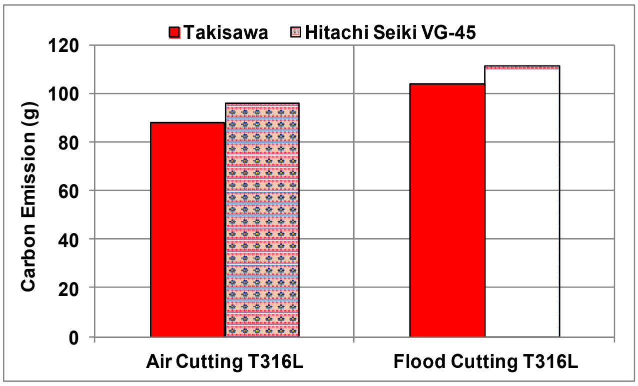

Figure 6: Carbon emission at low cutting speed of 650 rpm.

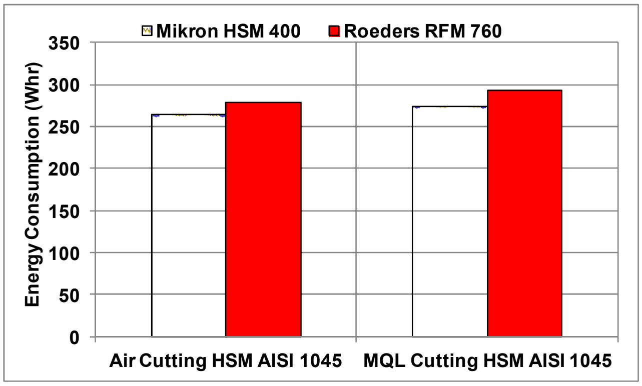

Figure 7: Energy consumption at 32000 rpm on AISI1045.

Figure 8: Carbon emission at high cutting speed of 32000 rpm.

The comparison for energy footprints for a similar machine located in different countries and executing a similar job is as shown in Figure 9, 10, 11 and 12. Singapore and the USA ranked proportionately to each other while the UK and Germany ranked proportionately in terms of carbon emitted.

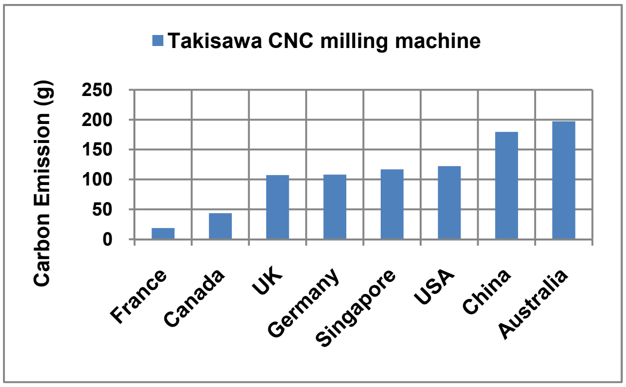

Figure 9: Direct energy derived carbon emission executing the same NC toolpath on Takisawa CNC milling machine in selected countries around the World based on 2010 CES^{TM} data [15].

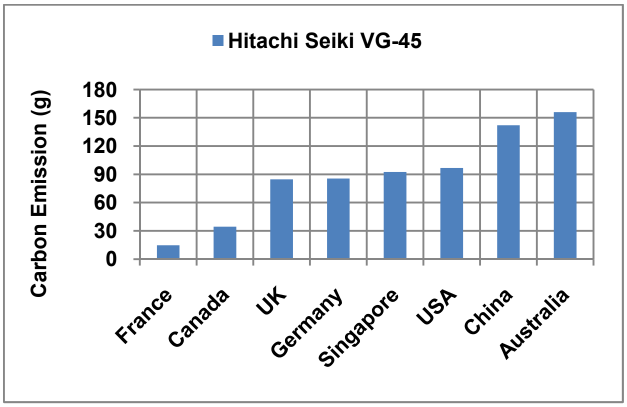

Figure 10: Direct energy derived carbon emission executing the same NC toolpath on Hitachi Seiki VG-45 in various countries around the World based on 2010 CES^{TM} data [15].

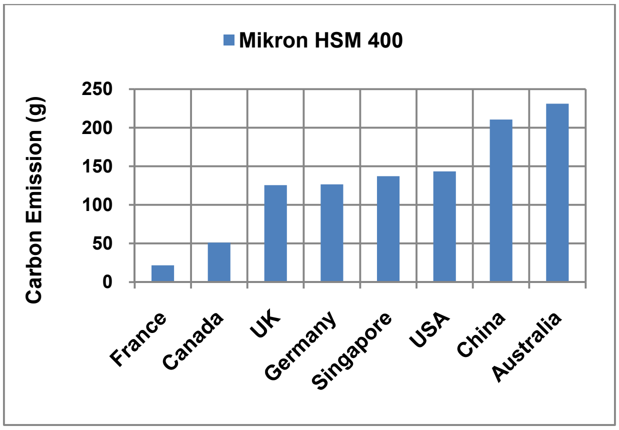

Figure 11: Direct energy derived carbon emission executing the same NC toolpath on Mikron HSM 400 in various Countries around the World based on 2010 CES^{TM} data [15].

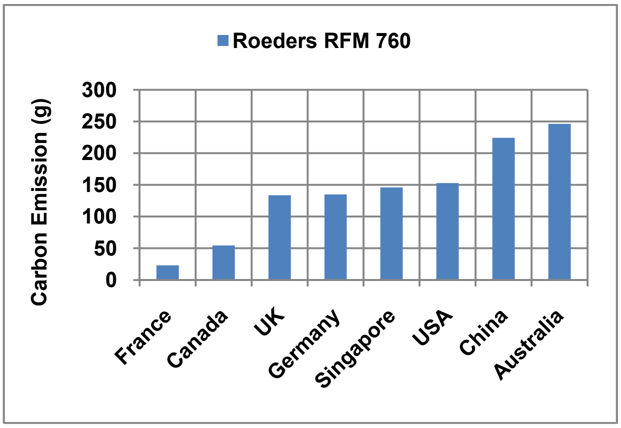

Figure 12: Direct energy derived carbon emission executing the same NC toolpath on Roeders RFM 760 in various Countries around the World based on 2010 CES^{TM} data [15].

Executing the same NC toolpath in other countries, assuming the same machine tool system has was used in those countries, shows that under a low spindle speed of 650 rpm, a machine located in France will be associated with the lowest direct energy derived carbon dioxide footprint. On this environmental burden argument, it would appear that Australia and China are the worst locations for a setting up a machine shop (unless machine tools that are significantly more energy efficient are made for these locations).

4 CONCLUSION REMARKS

The research work investigated the impact of machine tools and country carbon emission signature (CES^{TM}) on the energy demand and associated carbon dioxide footprint when executing a standardized NC toolpath. The following points were drawn from the study:

1. In mechanical machining energy demand by the machine tool dominates the total energy compared to the energy required at the tool-tip (actual) cutting. Thus the choice of machine tool, or the design of more energy efficient machine tools, can be a significant strategy for reducing the energy and CO_2 footprint of machined components.
2. The assessment of energy requirements for standardized tool paths showed 20.9% reduction when comparing the Takisawa to the Hitachi machine in conventional machining; and 6 % reduction when comparing the Roeder RFM 760 to the Mikron HSM 400 machines in high speed machining.
3. Although the energy demand when executing the standardized NC tool path was lower or moderately higher for machines located in Singapore the direct energy derived carbon footprint was higher for Singapore in both conventional and high speed machining due to the relatively higher carbon emission signature for Singapore as compared to the UK.
4. When more energy efficient machines are used with a typical 20% lower energy demand, their carbon emission signature can be significantly increased by moving the machine from one geographical location to another due to differences in carbon emission signature between nation states. This may increasingly

become a relevant consideration due to international mobility of capital and manufacturing businesses. Introduction of carbon emission penalties or quotas will make this even more critical.

5. If an identical machine tool is located in France, assuming all conditions are the same, the direct energy derived carbon footprint for machines located in Canada, the UK, Germany, Singapore, USA, China and Australia will be worse. This implies that France due to its high dependence on nuclear power has a competitive advantage as a greener manufacturing environment in the context of location of machine shops.
6. In optimizing the energy intensity of manufacturing operations, the designers of the machine tools to be used in higher carbon intensity geographical locations, have to make a greater impact in reducing the energy demand for each machine tool, if they are to match the carbon footprint for nation states that have higher percentage of carbon neutral electricity generation methods.
7. **Note:**

- The investigation reported here is based on carbon footprints derived from direct electrical energy requirements and does not take into account the embodied energy of inputs to the machining process or other stages in the product life cycle.
- The carbon emission signature varies for nation states depending on their energy split in a particular year.
- Within one country different geographical locations or facilities can have electricity that is generated from different sources and hence different carbon emission signature.
- The machine tools reported in this study are a selected range of machine tools that were available from the participating laboratories and do not represent the best technology available on the market or from the designers of the machine tools.

5 REFERENCES

[1] Kordonowy, D.N. (2002): A Power Assessment of Machining Tools, BSc Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA.

[2] Gutowski, T., Dahmus, J., Thiriez, A. (2006): Electrical Energy Requirements for Manufacturing Processes, in: Proceedings of the 13th CIRP International Conference on Life Cycle Engineering, Leuven, Belgium.

[3] Dahmus, J., Gutowski, T. (2004): An Environmental Analysis of Machining, in: Proceedings of the ASME International Mechanical Engineering Congress and RD&D Exposition, pp. 1-10, Anaheim, California, USA.

[4] Devoldere, T., Dewulf, W., Deprez, W., Willems, B., Duflou, J. (2007): Improvement Potential for Energy Consumption in Discrete Part Production Machines, in: Proceedings of the 14th CIRP International Conference on Life Cycle Engineering, pp. 311-316, Waseda University, Tokyo, Japan.

[5] Diaz, N., Redelsheimer, E., Dornfeld, D. (2011): Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use, Glocalized Solutions for Sustainability in Manufacturing, in: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, pp. 263-267, Technische Universität Braunschweig, Braunschweig, Germany.

[6] Vijayaraghavan, A., Dornfeld, D. (2010): Automated Energy Monitoring of Machine Tools, in: CIRP Annals - Manufacturing Technology, Vol. 59, No. 1, pp. 21-24.

[7] Rajemi, M.F., Mativenga, P.T., Aramcharoen, A. (2010): Sustainable Machining: Selection of Optimum Turning Conditions Based on Minimum Energy Considerations, in: Journal of Cleaner Production, Vol. 18, No. 10–11, pp. 1059-1065.

[8] Anderberg, S.E., Kara, S., Beno, T. (2010): Impact of Energy Efficiency on Computer Numerically Controlled Machining, in: Proceedings of the IMechE, Part B-Journal of Engineering Manufacture, Vol. 224, No. B4, pp. 531-541.

[9] Li, W., Zein, A., Kara, S., Herrmann, C. (2011): An Investigation into Fixed Energy Consumption of Machine Tools, in: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, pp. 268-273, Technische Universität Braunschweig, Braunschweig, Germany.

[10] Cao, H., Li, H., Cheng, H., Luo, Y., Yin, R., Chen, Y. (2012): A Carbon Efficiency Approach for Life-Cycle Carbon Emission Characteristics of Machine Tools, in: Journal of Cleaner Production, Vol. 37, pp. 19-28.

[11] Branker, K., Jeswiet, J., Kim, I.Y. (2011): Greenhouse Gases Emitted in Manufacturing a Product - A New Economic Model, in: CIRP Annals - Manufacturing Technology, Vol. 60, No. 1, pp. 53-56.

[12] Diaz, N., Choi, S., Helu, M., Chen, Y., Jayanathan, S., Yasui, Y., Kong, D., Pavanaskar, S., Dornfeld, D. (2010): Machine Tool Design and Operation Strategies for Green Manufacturing, in: Proceedings of the 4th CIRP International Conference on High Performance Cutting, pp. 271-276.

[13] Narita, H., Desmira, N., Fujimoto, H. (2008): Environmental Burden Analysis for Machining Operation Using LCA Method, in: Proceedings of the 41st CIRP Conference on Manufacturing Systems pp. 65-68, Tokyo, Japan.

[14] Jeswiet, J., Kara, S. (2008): Carbon emissions and CES™ in manufacturing, in: CIRP Annals - Manufacturing Technology, Vol. 57, No. 1, pp. 17-20.

[15] OECD/IEA CO_2 Emissions from Fuel Combustion 2012 - Highlights (Pre-Release) Available from: www.iea.org/publications/freepublications/publication/name,4010,en.html (accessed: November 2012).

[16] Department of Energy and Climate Change, Energy Digest of United Kingdom Energy Statistics (DUKES), Fuel mix disclosure data table, Available from: http://www.decc.gov.uk/en/content/cms/statistics/energy_stats/fuel_mix/fuel_mix.aspx (accessed: October 2012).

[17] Tan, R.B.H., Wijaya, D., Khoo, H.H. (2010): LCI (Life cycle inventory) Analysis of Fuels and Electricity Generation in Singapore, in: Energy, Vol. 35, No. 12, pp. 4910-4916.

[18] Mori, M., Fujishima, M., Inamasu, Y., Oda, Y. (2011): A Study on Energy Efficiency Improvement for Machine Tools, in: CIRP Annals - Manufacturing Technology, Vol. 60, No. 1, pp. 145-148.

[19] He, Y., Liu, F., Wu, T., Zhong, F.P., Peng, B. (2012): Analysis and Estimation of Energy Consumption for Numerical Control Machining, in: Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture, Vol. 226, No. B2, pp. 255-266.

[20] Balogun, V.A., Mativenga, P.T. (2013): Modelling of Direct Energy Requirements in Mechanical Machining Processes, in: Journal of Cleaner Production, Vol. 41, pp. 179-186.