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Greenhouse gases emitted in manufacturing a product—A new economic model

K. Branker [a], J. Jeswiet (1) [a,b,*], I.Y. Kim [a]

[a] Department of Mechanical and Materials Engineering, Queen's University, Kingston, Canada
[b] Australian National University, Canberra, Australia

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ABSTRACT

In this paper, we propose a machining microeconomic model that can optimize machining parameters and include all energy and environmental costs. A survey of microeconomic machining cost models is covered, with the result that a new cost model has been developed based on life cycle analysis (LCA) methodology. The scope includes the initial part production. Theoretical and actual experimental results are used to illustrate the model's implications with respect to carbon emissions and cost sensitivity. It is shown that for a manufacturing strategy, more certainty is required for inputs like carbon pricing to reduce financial risk. The limitations of the model, policy issues and future work are outlined.

1. Introduction

Green house gas (GHG) emissions, mainly carbon dioxide (CO_2) emissions, are on the global agenda with regard to climate change. Manufacturing operations are naturally energy intensive and electricity generated from fossil fuels is a major CO_2 contributor [1]. Life Cycle Assessment (LCA) is still a maturing methodology being used to consider product sustainability assessing the full range of environmental and social damages assignable to a product [1,2]. Increasing commodity prices and consumer pressure are driving environmentally conscious business strategy to gain economic advantage through effective energy and cradle-to-grave (LCA) product management [3,4]. The manufacturing industry is always concerned with finding optimum machining parameters, but is usually limited to cost, productivity and quality, excluding the environmental burden [5–8]. However, environmental costs like carbon pricing introduce another aspect for contract competition. For example, the growth of Enterprise Carbon Accounting software is being driven by cost reduction initiatives, government legislature and supply chain pressure for sustainability [9].

2. Literature review

LCA is an important concept that affects the economics of a product and when combined with existing manufacturing economic models, produces a more complete model. The method presented here improves the energy and environmental burden accounting in the initial manufacturing of a product.

2.1. Microeconomic cost models

Manufacturing and machining economic models can be divided into microeconomic and macroeconomic models [10,11]. This paper is concerned with microeconomic models that detail the cost per piece or component being machined and entails modifying or optimizing individual design or process parameters. Commonly optimized parameters to minimize machine cost are cutting speed and tool life [5,6]. A survey of 150 design and manufacturing companies revealed that more effective tools are required for cost estimation in product development [12]. With increasing emphasis upon CO_2 emissions, there is a need to review existing cost models to anticipate how manufacturers can deal with new costs, like carbon cost.

A survey of microeconomic cost models reveals that cost components or models can be divided into traditional (T) and non-traditional (NT) [13]. T cost models entail those direct costs associated with manufacturing, often not including energy and environmental considerations explicitly. These costs include labour, equipment, materials, overhead, tooling and material handling amongst others [5,14,15]. NT costs are due to energy, transportation and environmental burden [13]. Recent research revolves around energy and specifically CO_2 reduction as ways to achieve sustainable manufacturing, developing more terms and better quantification [1,13,16–25], thereby approaching a full cost accounting. However, fully accounting for environmental costs is still lacking in economic models. Also, linking ancillary or indirect energy costs to machining parameters is not clear.

2.2. Energy and environmental accounting

An important distinction is the classification of energy. It can be considered at the "process" and "plant" level [25]. Although Anderberg [13] uses direct and indirect energy to divide energy used in the manufacturing 'process', these terms regularly refer to that for the process versus the overhead facility in the plant [20,25]. Rahimifard [25] considers direct energy to be the sum of theoretical energy and the supporting auxiliary energy. The theoretical energy is the minimum energy required related to specific energy of the process [5,25,26].

Since microeconomic models are concerned with the process level, in this paper, the theoretical energy will be the direct energy

* Corresponding author.

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(E_D) and the energy for support systems will be the ancillary energy (E_A). Thus the direct and ancillary energy are associated with the process, whilst indirect energy is associated with maintaining the process (plant) environment.

The DE required for a cutting process is well documented [5,26]. The Numerical Control program of a mill can be used with workpiece and cutting tool models to get energy and other required process data [27]. A new minimum energy criterion was suggested when optimizing machining parameters, accounting for the direct and ancillary energy of a process and the embodied energy of the tool [23]. Similarly, it was suggested that minimizing the embodied product energy, fully accounting for direct and indirect energy, be used during manufacturing [25].

Most studies considering environmental burden usually use only CO_2 or GHGs as the pollutant, although many others exist. Narita [27] outlines and demonstrates an environmental burden analyzer based on LCA methodology to quantify the CO_2 footprint of a machining operation due to energy and other embodied carbon sources. The SIMTER project [28], is another simulation project, but goes beyond just CO_2 emissions. Their tool can be added to the larger machine monitoring framework, with the limitation being the accuracy of underlying databases and uncertainty in the underlying models and application of economics for planning and pricing decisions.

Various models and technologies exist and are being developed for real time tracking of energy and CO_2 footprint (e.g. [29]) or doing sustainable analysis of machining. However, without verification, the cost savings may not justify such investments [7] and a full costing of a product is necessary.

3. New LCA based microeconomic model

In general, detailed energy and environmental considerations are often lacking. An LCA based method [27] is used to develop a new economic model to investigate the impact of full accounting of costs in the manufacturing phase of a product's life cycle. Although only CO_2 emissions are considered, the framework allows for other environmental aspects to be added. The overall microeconomic model is a summation of several costs, as shown in Eq. (1), with the terms and supporting equations summarised in Tables 1 and 2.

$$C_p = C_m + C_s + C_l + C_t + C_{MD} + C_{MID} + C_{ED} + C_{EA} + C_{env} \quad (1)$$

The first four terms in Eq. (1) are directly related to the machining process and are not new and can be determined using workpiece and cutting tool models [5]. Process energy costs are excluded from the overhead costs. This is a logical extension of the model by [5] and models by [13,26,27]. The energy costs are left divided as direct and ancillary costs and the final term in the model is an aggregate of environmental costs, like carbon cost. The carbon cost or price, associated with a carbon regulation will be due to energy used in the process, the lubrication, other materials and other CO_2 emitting processes. The environmental cost term can be expressed as the summation of various environmental units per part knowing the cost per unit.

3.1. Components in the model

The first four terms in Eq. (1) are not new. However, the idling time can also be divided into a constant term (for loading and unloading) and a variable term for idle tool motion time such as tool travel and tool approach [6].

The direct material cost, C_{MD}, is simply the cost of the material used for the workpiece less the savings of left over material. Indirect material cost, C_{MID}, is for materials not included in the final product, such as coolant. The amount of indirect material used is related to the process time which is affected by the usage time, replenishing rates and type of each material [27].

The E_D cost is related to the minimum energy required to do the cutting process [5,26] and the cost of electricity [13]. The energy consumed can be determined several ways. Experimentally, where the energy consumed is measured and the electrical cost is known, whether fixed or at time of use. It can also be derived from knowing the efficiency of the operation. The E_D used can also be derived knowing the machine specifications and energy required to remove the material; see Eq. (2) [4,26].

$$E_D = (k \cdot \dot{v}) \cdot t_m \quad (2)$$

The E_A cost is related to the ancillary power that is ongoing during the entire process. It can consist of ancillary or peripheral equipment such as running computer, fans, unloaded motors, servos, including energy due to process inefficiencies like "axis jog" [23]. The E_A can be expressed as in Eq. (3):

$$E_A = P_0\left(t_s + t_m + \frac{t_c t_m}{T}\right) \quad (3)$$

where P_0 can be considered constant or a variable function [4,13,26]. This involves extracting the E_A from the total energy known. If the power required is considered constant, it is related to the running time of the process [27]. An aggregation of the electric consumption of the different peripheral devices knowing the power requirements and running time can be used [27].

Rahimifard [25] indicates the E_A can be determined or measured though empirical studies. Whilst measured data is presented, it is unclear how the E_A is related to process parameters apart from running time. Alternatively, energy use can be measured dynamically. Several energy monitoring devices are

Table 1
Summary of terms and equation components for Eq. (1).

Symbol	Cost term	Definition and sub-components	Equation		Ref.
C_m	Machining (process)	Labour cost of production operation and burden rate/overhead charge of machine (includes depreciation, maintenance, and indirect labour) for machining time.	$C_m = t_m \cdot K_m = t_m \cdot (L_m + B_m)$	(6)	[5]
C_s	Set-up (preparation)	Fixed figure in dollar per piece for mounting parts, preparing machines, etc.	$C_s = \frac{K_m}{N_p} \cdot t_s$	(7)	[5]
C_l	Workpiece and equipment handling	Costs for loading, unloading and handling the workpiece and equipment.	$C_l = K_m \cdot t_l$	(8)	[5]
C_t	Tooling	Cost of tool and tool holder, related to the tool and tool holder life. Can include tool change and grinding costs.	$C_t = \left(\frac{K_h}{N_h} + \frac{K_i}{0.75n} + K_m \cdot t_c + K_g \cdot t_g\right) \cdot \frac{t_m}{T}$	(9)	[5,13]
C_{MD}	Direct material	Cost of material used for the part	$C_{MD} = K_M \cdot MD$ (10)		
C_{MID}	Indirect material	Cost of lubricant, coolant, etc. used in the process to make the part	$C_{MID} = [K_{coolant} \cdot (CC + AC)] + [K_{lub} \cdot \mathrm{LO}] + \cdots$	(11)	[27]
C_{E_D}	Direct energy	Direct (theoretical) energy from electricity (or other) used in the machining process	$C_{E_D} = E_D \cdot K_E$	(12)	[13]
C_{E_A}	Ancillary energy	Cost associated with peripheral or ancillary equipment and background energy used in the process	$C_{E_A} = E_A \cdot K_E$	(13)	[13]
C_{env}	Environmental burden or cost	Can have various sub-components. This can include costs of CO_2 emissions, waste (disposal/recycling) and water use. This paper will focus on the cost burden of CO_2 emissions	$C_{env} = \left[\sum_{i=1}^{N}(BQ_i \times k_i)\right]$ *BQ*: burden quantity, *i*: specific burden index, *k*: burden unit cost	(14)	