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Energy efficient process planning for CNC machining ☆

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ABSTRACT

Machining is one of the major activities in manufacturing industries and is responsible for a significant portion of the total consumed energy in this sector. Performing machining processes with better energy efficiency will, therefore, significantly reduce the total industrial consumption of energy. In this paper, a framework is presented to validate the introduction of energy consumption in the objectives of process planning for CNC machining. The state of the art in process planning and energy consumption in manufacturing research is utilised as a basis for the framework. A mathematical representation of the logic used is presented followed by two sets of experiments on energy consumption in machining to validate the logic. It is shown that energy consumption can be added to multi-criteria process planning systems as a valid objective and the discussion on using resource models for energy consumption estimation concludes the paper. These experiments represent a part test procedure machining proposal for the new environmental machine standard ISO 14955 Part 3.

1. Introduction

Over the last 100 years, manufacturing has been changing with paradigm shifts to support advances in technology and to meet the emerging cultural and societal needs. This has seen the industry move through a number of phases: craft production, mass production, flexible manufacturing and personalised design and manufacture [1]. Today, a new industrial revolution is being conceived that will continue forever in the form of sustainable design and manufacture. This new revolution is starting to bring together new paradigm shifts from the early phase of energy conscious manufacturing to today's new vision for energy efficient production.

The drivers for this vision are obvious with governments worldwide recognising that energy demands continue to increase, with the international energy agency predicting an increase of 1.5% each year from 2007 to 2030 [2]; with the prediction that emerging economies such as China and India will account for half of this increase. A UK government white paper from 2007 concurs this prediction that on the basis of present policies, global energy demand will be more than 50% higher in 2030 when compared to 2006, with energy related greenhouse gas emissions to be around 55% higher [3].

Increased social awareness and scientific knowledge of energy usage resulting from the vast impact of the growing human population is increasingly forcing the regulatory bodies to encourage reduction of consumption in different sectors by different methods. These range from putting levies and taxes on the energy itself to introducing CO_2 emission allowance for large industrial consumers [2]. These regulations along with the high price of energy have provided a powerful incentive for research around the methods of reduction in energy consumption, especially in the highest consuming sectors.

Manufacturing is a major contributor in relation to other sectors. For example, in the UK, "Machinery and equipment" has been responsible for 2.45% of industrial consumption and more than 0.50% of the total energy consumption of the country [3].

As a result, energy related research is taking central stage in the European Commissions Framework 7 Manufacturing research programme termed *Manufuture* [4]. Energy is having an impact on numerous research areas from Energy Efficient Buildings to Green Cars [5]. At the forefront of the *Manufuture* vision is the Factories of the Future (FoF) initiative which is a €1.2 billion programme in which the European Commission and industry will support the development of new enabling technologies for EU manufacturing with cross-sector benefits and contributions to greener production. The EU Commission goal is to meet global consumer demand for greener, more customised and higher quality products through the transition to a demand-driven industry with lower waste generation and energy consumption [5].

This paper considers the critical aspect of energy efficiency in manufacturing and in particular process planning of products. Computer Aided Process Planning (CAPP) has continued to be developed for over 40 years with its early origins dating back to the 1960s. The focus of much of this early work was in optimising the

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Table 1
Categorisation of manufacturing analysis scales.

Level of analysis of manufacturing	Manufacturing analysis scale	Temporal decision scale
Supply chain management, enterprise asset management	Manufacturing supply chain	Days–hours
Production planning and scheduling	Manufacturing enterprise	Hours–seconds
Macro-planning	Manufacturing equipment	Hours–seconds–milliseconds
Micro-planning	Sub-components	Seconds–milliseconds
Process control	Tool–chip interface	Milliseconds

Adapted from [11].

operation planning and costs of production processes based on process parameters such as spindle speeds, feeds, depth of cut, tool wear.

Today's paradigm shift towards environmentally conscious production started with initial pioneering research in process planning, as early as 1995 by Sheng and Srinivasan [6]. This work has had some sporadic further developments over the last 15 years but the growing cost of energy combined with today's sustainable drivers towards energy efficiency provide new opportunities for researchers and industry to develop new energy modelling software to support energy efficient manufacturing resources throughout their life cycle. This paper aims to explore these challenges and provide a framework as the basis for future developments in using current generation of resources more effectively in terms of energy usage.

The paper is structured in 7 major sections. Following this introduction, a review of related literature in the area of energy consumption in machining is presented. A brief history of computer aided process planning, in general, and multi-criteria process planning, in particular, is provided which progresses to identify the environmentally conscious and green process planning and manufacture. A theoretical framework for energy efficient manufacturing is then provided, supported by a series of machining experiments on energy consumption in CNC machining. Finally the paper concludes with a discussion of the major aspects of the research and identifies avenues for further work.

2. Energy consumption in machining

Despite being a matter of concern for scholars and thinkers as early as the 10th century [7], the adverse impacts of human beings' activities on the environment were not taken seriously until the recent decades, when the public became aware of the severity of the issue. Manufacturing, the core of industrial activities, has naturally been a focal point in environmental impacts studies. Being a key element in manufacturing, machining has played a major role in measuring the magnitude of these impacts.

A great deal of research has been conducted at both system-level and process-level to evaluate the environmental impacts of machining and to find practical methods to reduce these impacts [8–10]. Environmental impacts of machining processes happen through use of energy, waste materials and chemical emissions [8].

The motivation for investigations regarding reduction in chemical emission and waste usually comes from legislation [9]. For example, efforts are being made to reduce the use of cutting fluids, as this is an important source of chemical pollution and waste in machining. Popke et al. [9] have introduced and investigated a method for cutting with a minimum amount of cutting fluid. The significance of their result is that there is a potential for economic benefit as a by-product of research purely driven by environmental motivations.

An event stream processing-based framework has been introduced by Vijayaraghavan and Dornfeld [11] to temporally analyse the energy consumption of machine tools and other manufacturing equipment. This framework identifies 5 different levels of manufacturing analysis scales, each with its own temporal decision scale, energy consumption characteristic and affecting parameters. Table 1 shows this categorisation.

A comprehensive system-level investigation of the environmental impact of machining has identified six different environment-effecting processes present in machining as:

- Material production
- Material removal
- Cutting fluid preparation
- Machine tool construction
- Tool preparation
- Cleaning

This study suggests that energy use is the main cause in the majority of the environmental impact of the identified activities in material removal processes. Additionally, since the energy consumed by machine tools is typically provided by the electricity grid, the true environmental impact of their electricity consumption must be calculated with the effects of electricity production and transfer being taken into account. The other significant point is that the energy consumed in the material production process can sometimes be much greater than the whole energy consumed during the material removal process. This is specifically correct for very energy intensive materials such as virgin aluminium utilised in higher size to weight ratio aerospace structures. However, for recycled steel or any other non-energy-intensive material, the energy used in material production and material removal processes are of the same order of magnitude [8].

The energy consumed in other processes in relation with the machining, like cutting fluid preparation, tool preparation, machine tool construction and cleaning is small in comparison with the two high-energy-consuming processes: material production and material removal. However, they can still have enormous environmental impacts through means other than their consumption of energy, e.g. chemical emissions [12].

The energy consumed in machining processes is a matter of investigation, not only for its environmental impact, but also as an indicator for other phenomena during the machining processes. Indirect monitoring of tool conditions by measuring the electrical power consumption of the machine tool is an example of such applications. This indirect measurement method has proven to be a low cost, highly reliable, flexible and quick method for tool condition monitoring [13].

A large number of researches have been done in the process control level to reduce the energy consumption in machining by improvement in tool–chip contact mechanics. Zolgharni et al. [10], for example, investigated the improvements in energy efficiency of machine tools by using Diamond-Like Carbon (DLC) deposited tools. This method was shown to be able to reduce the cutting power consumption of the machine by 36%.

However, the actual cutting energy used in the machine tool in material removal process accounts for only 15–25% of the whole energy consumed by the machine during the material removal process [8,11,14]. The rest of the energy is consumed in other parts