Energy Efficient Process Planning for CNC Machining

S. T. Newman, A. Nassehi, R. Imani-Asrai, and V. Dhokia
Department of Mechanical Engineering, University of Bath, BA2 7AY, UK

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 IS014955 Part 3.

Keywords

Computer Aided Process Planning; CNC Machining, Energy Efficiency

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 percent of industrial consumption and more than 0.50 percent 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 operation planning and costs of production processes based on process parameters such as spindle speeds, feeds, depth of cut, tool wear etc .

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 [8,9,10]. 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 it is shown 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 percent 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 inside the machine; the controller, fluid pump, fan and other ancillary devices are responsible for a part of the total energy consumed by the machine [14]. The spindle’s free rotation and machine’s idle running consumed energy at times when no actual cutting is in progress. The gap between the energy

consumed by the machine tool and the actual energy required for material removal is the total potential for saving energy in the CNC metal Cutting process.

There are many different possible approaches to use the potential for energy saving in machine tools explained above. A study by Neugebauer et al. [15] shows that the share of ancillary devices and supporting systems in the total energy consumption of the machine tools typically increases when the size of the machine tool grows [15]. Therefore, choosing smaller machine tools in planning and scheduling phases can potentially reduce the energy consumption for the same machining job. The same study shows that the dynamic parameters of the machine tool can affect its power demand which shows another possible approach towards saving energy in planning level [15].

Another planning-level approach to reduce the energy consumption during machining process is the minimisation of the energy consumed during the cutting time by choosing the optimum cutting parameters [14,16,17]. Observations show that the total energy consumption- and therefore the efficiency- of a machine tool during a cutting process depends on the choice of process parameters. Therefore, finding the optimum combination of process parameters for doing a particular cutting job can be regarded as nothing more complex than a mathematical optimisation problem [14]. A mathematical model for the machine tool's energy consumption as a function of its working parameter is needed to complete the formulation of the optimisation problem [17]. This model can be constructed by curve fitting methods if sufficient experimental data is available. A Response Surface Methodology (RSM) was used by Draganescu et al [17] to model a machine tool's efficiency in this manner.

The advantage of the RSM method is that it provides a well-fitting mathematical model of the machine tool's efficiency, without the difficulty of taking the physics involved into account. This can, however, be regarded as a disadvantage at the same time, as none of the terms appearing in the mathematical model have any physical meaning. So, despite being useful in reducing the energy consumption of machine tools, the RSM method cannot provide a tool for further investigations about the machine tools' efficiency.

3 Computer Aided Process Planning(CAPP)

3.1 Evolution of CAPP

Computer aided process planning (CAPP)'s inception dates back to the mid 1970s. Though the notion of using computers to aid process planning was introduced by Niebel [18] in 1965, one of the major pioneers of CAPP was Wysk [19] who in his PhD thesis of 1977 outlined an automated process planning and selection program: APPAS. These sparked a plethora of CAPP research and systems with numerous CAPP developments in the 1970s and 1980s which are reported by Weill, Spur and Eversheim [20] and Alting and Zhang [21] in their early reviews. The computer integrated manufacturing systems push of the 1990s saw commercial CAPP systems being integrated within CAD/CAM and tooling systems [22] for micro-process (machine level) planning together with macro process planning linking process planning and production planning and control [23]. In parallel with these commercial system developments, the academic community has been exploring Artificial Intelligent and Knowledge Based techniques [24] combined with CAPP research in design and manufacturing features [25]. One of the final CAPP surveys by Marri et al. [26] illustrates the significant reduction in systems since the 1980s. Today there is an emerging need to integrate process planning and other factory software systems to enable real time planning and decision making based on the current and predicted status of the factory shopfloor.

3.2 Energy Conscious and Energy Efficient CAPP

One of the first papers to recognise the need to measure energy usage and the need for consider energy planning in the machining process dates back to 1979 [27]. From this initial investigation it wasn't until 1995 when Sheng et al. [6] outlined their environmentally conscious multi-objective approach to process planning. In this approach they identify a feed forward model which takes into account environmental factors such as process energy, process time, fluid coated on chips, evaporated fluid, tool scrap fluid mist, chip volumes and tool particles. This information is fed into an environmental impact model where a score for each machining operation is generated and fed into a process planning module with process energy used and

process time and surface quality requirements to generate machining process parameters. The model underpinning the approach is detailed by Munoz and Sheng [28] and extended based on feature based case study components in 1999, exploring environmental planning at the micro (ie. cutting tool parameters) [29] and macro planning (ie. setup and feature sequencing) [30] levels.

The work of Dahmus and Gutowski [8] reported in 2000, also has a major influence on process planning where they present a system-level environmental analysis of machining. This work describes an analysis together with a breakdown of energy usage for different machine tool types from manual machines to modern machining centres. The latest work on CAPP relates to systems to support Green manufacturing with a CAPP system that takes into account Optimization of energy consumption as part of the planning process [31].

In 2009 research reported by Jin et al [32] provides a multi-objective optimisation model for environmentally conscious CAPP. This paper outlines a mathematical model that takes into account materials, environmental data and environmental impact of the materials based on existing commercial database tools namely ECO-SCAN, IDEMAT to compute an environmental score for each tooling operation. This approach combined with the approach by Xu and Li [33] provides a basis for possible new goal oriented multi-parameter approach to represent a process parameter selection at multi-levels incorporating both micro and macro decision levels incorporating process knowledge with mathematical logic.

4 A theoretical framework for energy efficient process planning

It has been established that energy is used in a variety of manners in CNC machining. The vast majority of the machines used in the industry are powered by 3-phase electricity. As mentioned above, the energy is used not only in driving the mechanical elements of the machine directly related to the cutting process, but also to run auxiliary devices such as coolant dispensing mechanisms and electronics.

In order to make the metal cutting solution more energy efficient, a number of overall approaches can be adopted. These include: redesigning machines and controllers, redesigning controller software, adding external devices to regulate energy usage and finally, more efficient use of the currently available resources.

4.1 Redesigning CNC machines and controllers

Historically, CNC machines have been designed with speed and accuracy as the main objectives. However, a high speed accurate machine is not necessarily an energy efficient machine. Theoretically, by introducing energy efficiency as one of the criteria in the design and development process of CNC machine tools, it would be possible to improve their energy efficiency. Several EU research projects such as DEMAT [34] and NEXT [35] together with International initiatives like CO2PE! [36] aim to achieve this goal. As the current machines use about 25% of the given power in the machining process, substantial gains in energy efficiency can be expected from the success of these efforts.

4.2 Redesigning controller software

Current controller software is designed to drive the numerous axes in a machine tool with precision and speed. Modern controllers may include additional algorithms to avoid collisions and contain fault diagnosis routines. There is no major consideration of energy usage in the current incarnation of these systems. Theoretically, by developing more intelligent controllers that can predict the energy usage of various interpretations of the control instructions, it would be possible to select the most efficient interpretation given the speed and precision requirements. This could lead to energy saving in the process.

4.3 Additional external energy-saving devices

In lieu of hardware and software redesign, it would be possible to add certain energy saving devices to CNC machine tools to conserve energy [37]. These devices switch off power to the elements of the machine that are not under active use and therefore save power when the machine is idling. This approach allows savings to be made in existing manufacturing facilities without incurring huge costs. The maximum savings achievable using this technique is debatable and outside the scope of this paper.

4.4 More efficient use of current resources

The above approaches all entail modification of manufacturing resources in varying scales. While significant energy savings are attainable using the above methods, there are substantial costs associated with the necessary upgrades, refits and overhauls. This paper suggests that it may be possible to make more energy conscious use of the current available resources by considering the energy use as a criterion in process planning.

4.5 Validation of energy saving through process planning

As mentioned in 3.1 there have been numerous works of research in multi-criteria process planning. These works of research show that it would be possible to add additional criteria in choosing the best process for manufacturing a component using CNC machines.

Let *Workpieces* represent the entire set of raw blocks of material and workpieces. This infinite set includes every possible geometry made from every possible material with every possible set of tolerances and characteristics. Let *Operations* represent the set of all possible manufacturing operations using CNC machines. Each operation is defined as the mechanical interaction of a single cutting tool and a workpiece on a single machine controlled by a single toolpath with a constant feedrate, depth of cut, spindle speed and time. Each operation can therefore transform a workpiece to another workpiece and thus can be defined as a function[1]:

$$Operations : Workpieces \rightarrow Workpieces \quad (1)$$

Manufacturing often involves a sequence of operations. The set of finite sequences of Operations can be defined as:

$$\operatorname{seq} Operations == \{s : \mathbb{N} \pfun Operations \mid \exists n : \mathbb{N} \bullet \operatorname{dom} s = 1 \mathinner{..} n\} \quad (2)$$

Where $A \pfun B$ denotes the set of all finite functions from A to B:

[1] The logic notation used within this paper is that of Z [38]

$$A \twoheadrightarrow B == \{f : A \rightarrow\!\!\!\!\!\!\rightarrow B \mid \operatorname{dom} f \in \mathbb{F}\, A\} \tag{3}$$

In order to assess the effect of a series of operations on a workpiece the function *Manufacture* can be defined as:

$$\begin{array}{l} \_Manufacture\_ : \operatorname{seq} Operations \rightarrow (Workpieces \rightarrow Workpieces) \\ \hline \forall\, s : \operatorname{seq} Operations \bullet Manufacture(s) = s(1) \fatsemi s(2) \fatsemi \ldots \fatsemi s(\#s) \end{array} \tag{4}$$

For simplicity, only linear and sequential processes will be addressed in this paper. Similar reasoning can be applied to parallel processes. Based on this definition, any manufacturing process can be defined as a sequence of operations that has an effect on at least one workpiece:

$$Processes = \{s : \operatorname{seq} Operations \bullet \operatorname{dom} Manufacture(s) \neq \emptyset \land \operatorname{ran} Manufacture(s) \neq \emptyset\} \tag{5}$$

Two processes are considered to be *interchangeable* with respect to a specific workpiece if their effect on that workpiece is the same. The symbol for interchangeability is introduced as:

$$\begin{array}{l} \forall\, p, q : Processes \bullet \forall\, w : Workpieces \bullet p \approx^{w} q == w \in \operatorname{dom} Manufacture(p) \\ \land\ w \in \operatorname{dom} Manufacture(q) \land Manufacture(p)(w) = Manufacture(q)(w) \end{array} \tag{6}$$

In its most general sense, process planning is choosing a process among feasible options such that a certain function of that process such as time or tool wear is minimised. It is therefore possible to formulate process planning for manufacturing component *x* out of workpiece *w* as an optimisation problem:

$$\begin{array}{l} \text{Minimise } f(p \in \{q : Processes \bullet x \in \operatorname{dom} Manufacture(q) \land Manufacture(q)(x) = w\}) \\ \text{Subject to} \\ \qquad \text{Resource availability for every operation in } p \end{array} \tag{7}$$

In order to introduce energy consciousness into process planning, the energy usage function *e* should be introduced as a component of the objective function *f*. In order

for introduction of *e* as a valid component of *f*, it is necessary to prove that it differentiates between different processes. This can be proven by showing that there are at a least two interchangeable processes p and q in which the energy usage is different. In other words:

$$\exists\, p, q : Processes \bullet \exists\, w : Workpieces \bullet (p \approx^{w} q) \wedge e(p) \neq e(q) \quad (8)$$

In the following section, an experiment has been designed where the energy usage of two interchangeable processes have been measured and shown to be different.

5 Experiments on energy consumption of interchangeable machining processes

The authors have defined two sets of experiments to investigate that if interchangeable machining processes necessarily consume the same amount of energy. In the case of observing a difference in the consumed energy, the scale of this difference would decide if further investigations are going to be worthwhile.

These two sets of experiments represent the case of finish cutting and semi finishing of aluminium. In each of these two sets of experiment:

Four identical slots were machined out of a block of aluminium as shown in figure 1. Slots were cut by the same tool and the same spindle speed. The final depths of slots were all the same and equal to 12 mm. The slots were cut in multiple passes with each slot being cut as a result of passes of the same depth. The number of cuts *N,* and their depths of cuts *h*, for each slot were calculated subject to the condition that the final depth of the slots was 12 mm. Therefore,

$$Nh = 12mm \quad (9)$$

Additionally, the feed rates *f*, were calculated in a way to keep the total cutting time of slots equal.

$$\frac{Nl}{f} = cte \quad (10)$$

With *l* being the length of the block and slots. Equation 10 can be written as:

$$hf = cte \quad (11)$$

The feed rates, depths and number of cuts for each slot in the case of finishing are given in table 2. The same sets of data for the case of semi finishing are presented in table 3. These were chosen to be consistent with conditions in equations (9) and (11). A list of the definitive elements of the experiment set up, e.g. machine tool, material, etc., is shown in table 4. The total consumed power of the machine was measured during the experiment at the electric power entry of the machine. Since the feed rates and depths of cut were designed to make the total cutting time of all slots equal, the total energy used to cut each slot is proportional to the average power consumption of the machine while cutting that slot. Therefore, any difference between the power consumption of the machine during cutting different slots can be translated into the same difference in total energy consumed to cut those slots. The results of these sets of experiments are discussed in the next sections.

5.1 The case of finish cutting of aluminium

The first experiment was designed to represent very light cutting conditions, i.e. finishing. In this experiment the rate of material removal was designed to be 0.48 cm^3/s. The complete description of the parameters is given in table 2.

As shown in figure 2, the machine consumes 2.81 kW when the spindle is rotating at the working speed of 10000 rpm and is not cutting material, as shown at the dashed line in figure 2.

The first slot was cut with 1mm depth of cut. The depth was increased for each slot, so the last slot was cut by passes of 4mm depth. Power was automatically read every 6 seconds. From the power reading numbers 1 to 68, roughly, every 17 power readings relates to one of the slots. The average power consumption of the machine during the cutting process for each slot is given in the table 5.

The data in table 5 can be represented in a graph as shown in figure 3.

Since the total cutting time of all 4 slots are the same, the ratios of the consumed power, is exactly the same as ratio of the energy consumed during cutting slots.

The difference in power consumption in the first and the last cuts is 0.20 KW. This is about 6% of the total power consumption of the machine.

The graph in figure 3 is monotonic and almost linear over the investigated depth of cut which shows that the difference is likely to keep growing outside the range of depth.

Considering the fact that the machine consumes 2.81 KW of power when it is running free at the desired speed of 10000rpm, it may be concluded that the additional power consumption is due to the cutting process. This additional power is listed in the table 6.

As mentioned above, 2.81 kW of power is used by the machine while just rotating the spindle freely, and this represents more than 80% of the average power consumption of the machine during the cutting processes in this experiment. The additional power is spent as a direct result of the cutting process. Table 6 also shows that the relative difference in the additional power consumption due to actual cutting is about 40%. This shows that the achievable saving in the total energy consumption for more power demanding processes- higher loads- is likely to be more than that of this experiment, because in high load operations the share of actual cutting process in the total power consumption of the machine tool is considerably larger than in finish cutting. This was shown to be a correct prediction by the results of the second experiment which was designed to investigate higher loads – semi finishing – and will be discussed in the next section. In that experiment the difference between the cutting power of the highest consuming and the lowest consuming processes rose to 15% of the total power consumption of the machine- from the 6% measured in the finishing case.

Using the data in table 5, it is possible to calculate the energy consumed by the machine for removing a unit volume of material. The energy consumed per unit volume of removed material can be written as:

$$e = \frac{P}{fhD} \qquad (12)$$

This was calculated for all 4 slots and the results are presented in table 7.

Taking an average of about 7kJ/cm^3 from table 7, for the energy per unit volume removed for aluminium, this can be compared with the data in table 8, presented by Dahmus and Gutowski [8] for a range of machine tools used to cut aluminium.

As identified above, the experiment has been designed in the lower load range of machine capability typically used by small metal working companies for finish cutting, where the material removal rate is much lower than the cases previously investigated [8]. As previously outlined, the consumed energy per unit volume of removed material is expected to fall for higher loads. To investigate this, another experiment was designed for higher cutting loads. The results of this experiment are presented in the next section.

5.2 The case of semi-finishing cutting of aluminium

This experiment was designed to investigate the case of cutting aluminium at a relatively higher rate of material removal semi finishing. Instead of 0.48cm^3/sec, which was the case for the previous experiment, the rate of material removal was designed to be 2cm^3/sec for the second set of experiments which is closer to the range presented in table 8. The designed cutting parameters for this experiment are presented in table 3 above.

The tool and the machine tool are the same as those of the previous case. The only difference is that this time the spindle speed was decided to be 6000 rpm instead of 10000 which was the case in the case of light cutting experiment. The values of the power consumed by the machine tool during the cutting processes are presented in table 9 and figure 4.

The difference between the highest and lowest consuming processes is much larger in this case and is more than 0.50 kW. Moreover the magnitude of the relative difference in power consumption – largest difference in power consumption divided by the smallest absolute power consumption – has risen in comparison to the previous case to about 15%. This proves the prediction made during the discussion in the previous section about the likeliness of rise in the relative difference of power consumption for higher cutting loads.

The other major difference is that the specific energy consumption per unit volume of removed material in the case of heavy cutting is much smaller than in the case of light cutting which was expected. The values for the specific consumed energy is presented in Table 10.

5.3 The case of cutting a multi-featured aluminium part

To investigate the hypothesis of different energy consumption in interchangeable processes for a more realistic part, a multi-featured part was designed and cut out of an aluminium block. A photograph of the final part is presented in figure 5.

Figure 5. Multi-featured part designed for the energy consumption experiment

This part has 5 features, which, in cutting order, include:

- Outer path milling cut with a 16mm slot mill, 10mm deep
- Double crescent pockets cut with a 10mm slot mill, 4mm deep
- Rectangular pocket cut with a 6mm slot mill, 6mm deep
- 4 large corner holes drilled with a 12mm drill, 4mm deep
- 4 small middle holes cut with a 4mm drill, 8mm deep

Two interchangeable processes were designed for cutting the above part. In both processes, the drillings are performed identically. The difference was designed to be in the slot cuttings. In the first experiment slots were cut with 1mm depths of cut and 1000mm/min feed rates. In the second experiment the depths of cut of slots were doubled to 2mm and the feed rates were brought down to half, 500mm/min. As such, the material removal rate and the cutting time of each feature would remain the same in both experiments, hence the equality of the total cutting time and interchangeability of the two processes.

The power consumption of the CNC milling machine was measured during both experiments. The average power consumption of the machine tool during the milling processes, which were designed to be different in feed rate and depth of cut, was calculated based on the results of the experiments. The results are presented in table 11.

Table 11. Power consumption of the machine tool during the cutting of non-drilling features

The power consumption of the machine tool is higher in the case of low feed rate-high depth of cut, which is in compliance with the results of the previous experiments. The relative difference, however, is not particularly large, which is mainly due to the both depths of cut being rather small.

5.4 Conclusions from the experiments

The experiments discussed in this section prove that the energy consumption of two interchangeable processes may differ considerably. This proves that the energy consumption of cutting processes can be used as a criterion in process planning. This also proves that even without changing the process plan, there exists a notable opportunity for energy saving in cutting processes. Changing the process plan, considering the energy consumption as one the design criteria, will result in much larger energy savings.

Comparison between the two cases of finish cutting and semi finishing shows that changing the cutting parameters can result in larger change in energy consumption for those interchangeable processes with higher loads, i.e. higher rates of material removal. Therefore, there is more energy saving opportunity in high load metal cutting processes.

The other major observation is that the specific energy per unit volume of removed material is considerably smaller in semi finishing than in finish cutting. Therefore, it is expected that, generally, switching to heavy cutting, i.e. higher rates of material removal, can be, roughly, regarded as a way of saving energy in metal cutting. This, however, needs to be investigated further and is not necessarily correct in all ranges of material removal rates.

6 Discussion

6.1 Energy consumption in manufacturing

The previous research has shown that among all the activities involved in metal working manufacturing, two specific activities of material production and material removal are responsible for the majority of the total consumed energy and therefore and need to be further investigated [8]. Enhancing the tool-chip contact conditions for reducing energy consumption has been investigated [16], but other research shows that the material cutting process itself uses only about 20% of the total energy consumed by the machine during the cutting process [8,14,11]. In addition to the approach taken in this paper, further opportunities for saving energy in machining have been investigated by Neugebauer et al. [15] by using the smallest machine size available to manufacture the part. Planning-level approaches to energy saving in machining has been already investigated and shown by choosing appropriate cutting parameters, considerable amounts of energy savings are achievable [14,16,17].

The current mathematical models, as shown in the eye of figure 6, which represent energy consumption of the machines have been constructed by purely statistical curve fitting and do not represent any physical aspect of the sources of energy consumption inside the machine. A mathematical model based on the physical model of the machine can provide a powerful tool for reducing the energy consumption. Such a model, as shown in the pupil of the eye of figure 6, would represent the interactions between the machine's sub-systems during a cutting process. Moreover, the model can be used for integration of the consumed energy into process planning as a new predictable criterion. It can also be used for further investigation for machine tool efficiency by identifying the percentage of different energy consumption sources inside the machine. The different mathematical expressions in such a model can interpret the energy consumption through specific mechanisms such as friction, electrical resistance, etc.

6.2 Computer Aided Process Planning

Though, the authors have reviewed a significant body of research related to energy conscious and efficient in machining, there still exists enormous opportunities for

energy modelling and analysis in other manufacturing sectors. Though it should be recognised that the energy aspects are of course of growing interest in process planning but are not the prevailing information to make a decision concerning the cutting strategy and the optimization of the cutting conditions.

As process planning is part of the entire product development process, the need for energy conscious CAPP to be an integral part of product development is essential. Future CAPP systems will be required to access the integrated body of manufacturing knowledge existing in the enterprise such as that suggested in the universal manufacturing platform by Newman and Nassehi [39].In such a platform, CAPP system's would have access to process data, and also an integrated representation of the entire body of the manufacturing information including resources and product data. This requires the necessity to have a standardized way for modelling manufacturing resources [40]. Currently, there is a lack of models that represent the manufacturing resources, not only in their process and technical capability, but also taking account energy consumption [41]. These resource models not only have to represent the nominal capability and energy consumption of the equipment, but have to also be able to represent actual capability throughout their lifecycle.

6.3 Experimental results

6.3.1 Slot milling experiment

In this experiment, the authors have performed 4 interchangeable processes all of which result in the same slots of 12 mm deep, 16mm wide all along the block. The total time of cutting is also the same for all 4 slots. However, the relative difference in the total energy consumption is a considerable amount of approximately 6%. This accounts for almost 40% change in the power consumed for actual cutting, which makes it likely to experience more relative difference in the total power consumption at higher loads due to change in depth and feed, keeping the time for machining each slot constant. The important outcome of the results of this experiment is that even with keeping the total time of the process (operation) constant, there is still a huge opportunity for energy savings by only changing the process parameters. It is obvious that if the constraint of constant time is removed, i.e. the processes are not interchangeable anymore, even more energy savings become possible.

6.3.2 Multi-featured part experiment

In this experiment the authors put their hypothesis to a more realistic test. A multi-featured part was designed and was cut twice with different, but interchangeable, processes. The nominal cutting time was therefore the same for both experiments. Although the difference between the two interchangeable processes was minimal – 1mm and 2mm depths of cut – a substantial difference of more than 1.7 percent in the power consumption of the machine tool during cutting of different features was measured, which confirms the authors' hypothesis.

6.4 Proposed Test Procedure for IS014955 –Part 3

A new environmental standard ISO 14955 [42] is currently being developed by ISO/TC 39/WG 12 Environmental Evaluation of Machine Tools. This standard consists of 4 major parts as outlined below:-

i) ISO 14955-1 : Eco-design methodology for machine tools (working draft available)

ii) ISO 14955-2 : Methods of testing of energy consumption of machine tools and functional modules

iii) ISO 14955-3 : Test pieces/test procedures and parameters for energy consumption on metal cutting machine tools

iv) ISO 14955-4 : Test pieces/test procedures and parameters for energy consumption on metal forming machine tools

The experiments outlined above represent a proposal for part-3, as the machining of basic features (as opposed to arbitrary example parts) it makes it possible to create a baseline for energy requirements of each geometric feature (i.e. hole, pocket slot) on a given machine. Once these baseline figures are established – with the assumption that energy consumption of a machine tool is an additive function and has the superposition property – the energy requirement of a more complex part can be estimated by adding the requirements for individual features on the part. Investigation of the superposition property in machine energy usage is outside the scope of this current paper but is recognised as an important piece of work for the future. However, based on intuition, some work is starting based on the assumption that this property holds and can be used for assessing energy usage in machine tools.

7 Conclusions and Future Work

Manufacturing is a major contributor to the industrial energy consumption which is predicted to increase in the next 30 years. This paper has identified :-

- The theoretical framework outlined in the paper provides a powerful basis for mathematical representation of energy efficiency for process planning.
- The experiments show that the energy consumption of interchangeable machining processes can differ significantly, by at least 6% of the total energy consumption of the machine in low loads and is likely to grow to 40% at higher loads.

Though, the authors have reviewed a significant body of research related to energy conscious and efficient in machining, there still exists enormous opportunities for energy modelling and analysis in other manufacturing processes and sectors. This requires both industry and government to jointly develop new legislation and standards focused on energy efficiency for manufacturing resources. One approach to support this view is provided by Rahimifard et al [42] where they provide a detailed analysis of energy usage of products throughout the factory. Such approaches combined with new legislation combined and additional standards for energy efficiency for industrial buildings (factories) could form the next generation of world leading energy-independent factories, which will form a major part of the industrial revolution for reducing the global energy usage over the next 20 years.

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Table 1- *Categorisation of manufacturing analysis scales (Adopted from [11])*

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-Second-milliseconds*
Micro-planning	*Sub-components*	*Seconds-milliseconds*
Process control	*Tool-chip interface*	*milliseconds*

Table 2: *Depths of cut, feed rates and number of cuts for each slot cut during the experiment*

Slot number	***Depth of cut, h (mm)***	***Feed rate, f (mm/min)***	***Number of cuts, N***	***Rate of material removal, MRR (cm^3/s)***
1	*1*	*1800*	*12*	*0.48*
2	*2*	*900*	*6*	*0.48*
3	*3*	*600*	*4*	*0.48*
4	*4*	*450*	*3*	*0.48*

Table 3: *Set up description of the experiment*

Elements of experiment set up	***Description***
Block size	*230mm X 150mm X 1.5in*
Material	*Aluminium alloy 6042*
Machine	*Dugard Eagle 850 VMC*
Tool	*16mm high-speed steel*
Final slot depths	*12mm*
Slot lengths	*230mm (Whole length of the block)*
Spindle speed	*10000 rpm*

Table 4: *The average power consumption of the machine during the cutting processes, case of light cutting of aluminium*

Depth of each cut (mm)	***Number of cuts***	***Final depth of slot (mm)***	***Total power ± 0.03 (kW)***
1	*12*	*12*	*3.28*
2	*6*	*12*	*3.37*
3	*4*	*12*	*3.42*
4	*3*	*12*	*3.48*

Table 5: *The excess power consumed for cutting*

Depth of cut (mm)	***Additional power due to cutting (kW)***
1	*0.47*
2	*0.56*

3	*0.61*
4	*0.67*

Table 6: *Energy consumed per unit volume of material removed, case of light cutting of aluminium*

Depth of cut (mm)	***Energy per volume removed material (kJ/cm^3)***
1	*6.83*
2	*7.02*
3	*7.12*
4	*7.25*

Table 7: *Consumed energy per unit volume aluminium removed for some machine tools. Adapted from [8]*

Machine tool (year built)	***Consumed energy per unit volume aluminium removed (kJ/cm^3)***	***Rate of material removal (cm^3/sec)***
Production machining centre (2000)	*14.2*	*20*
Automated milling machine (1998)	*2.3*	*5*
Automated milling machine (1988)	*4.7*	*5*
Manual milling machine (1985)	*4.9*	*1.5*
*Dugard CNC milling machine (2009)**	*7**	*0.48**

**: Data from the authors' experiment*

Table 8. Parameters of experiment for the case of heavy cutting

Slot No	***Feed (mm/min)***	***Depth (mm)***	***Number of cuts***	***Final depth of slot (mm)***	***MRR (cm^3/sec)***
1	*2500*	*3*	*4*	*12*	*2*
2	*1875*	*4*	*3*	*12*	*2*
3	*1250*	*6*	*2*	*12*	*2*
4	*625*	*12*	*1*	*12*	*2*

Table 9. The average power consumption of the machine tool during the cutting processes, case of heavy cutting of aluminium

Depth of each cut (mm)	***Number of cuts***	***Final depth of slot (mm)***	***Total power ± 0.03 (kW)***
3	*4*	*12*	*3.57*
4	*3*	*12*	*3.85*
6	*2*	*12*	*3.94*
12	*1*	*12*	*4.09*

Table 10. The specific energy for removing material for each cutting process, case of heavy cutting of aluminium

Depth of cut (mm)	***Energy per volume removed material (kJ/cm^3)***
3	*1.78*
4	*1.92*
6	*1.97*
12	*2.04*

Table 11. Power consumption of the machine tool during the cutting of non-drilling features

Machine tool power consumption	***High feed-low depth case (W) ±0.3%***	***Low feed-high depth case (W) ±0.3%***	***Relative difference (percent) ±0.4***
Outer path milling	*2479*	*2483*	*0.2*
Crescent pockets	*2687*	*2719*	*1.2*
Rect. pockets	*2662*	*2707*	*1.7*

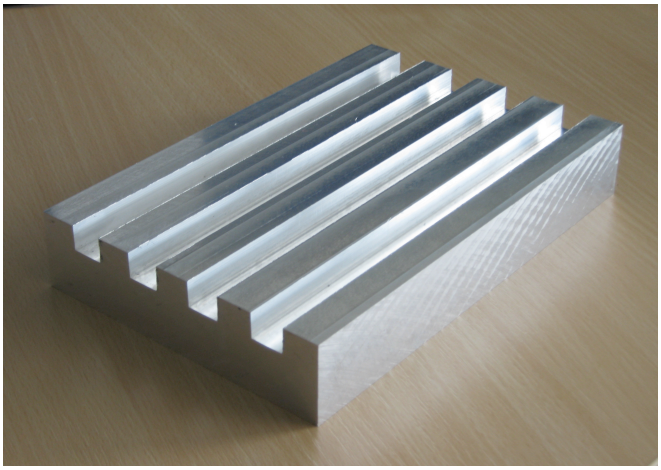

Figure 1: *One of the aluminium blocks cut during the experiments*

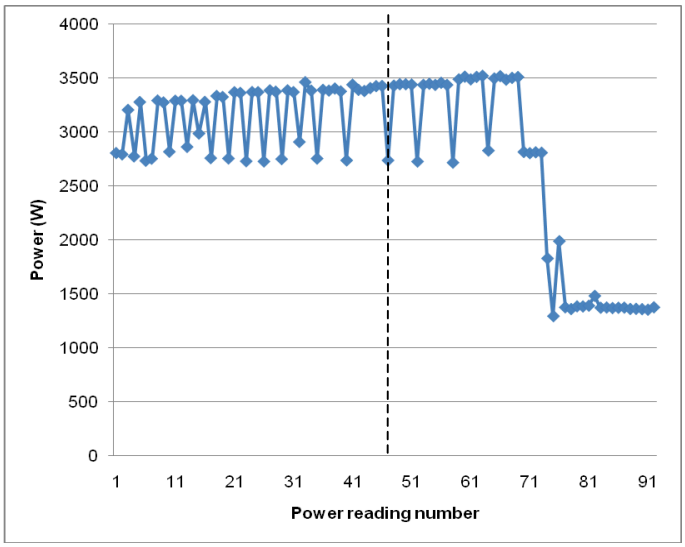

Figure 2: *Power consumption of the machine as read by the power measurement device – case of finishing*

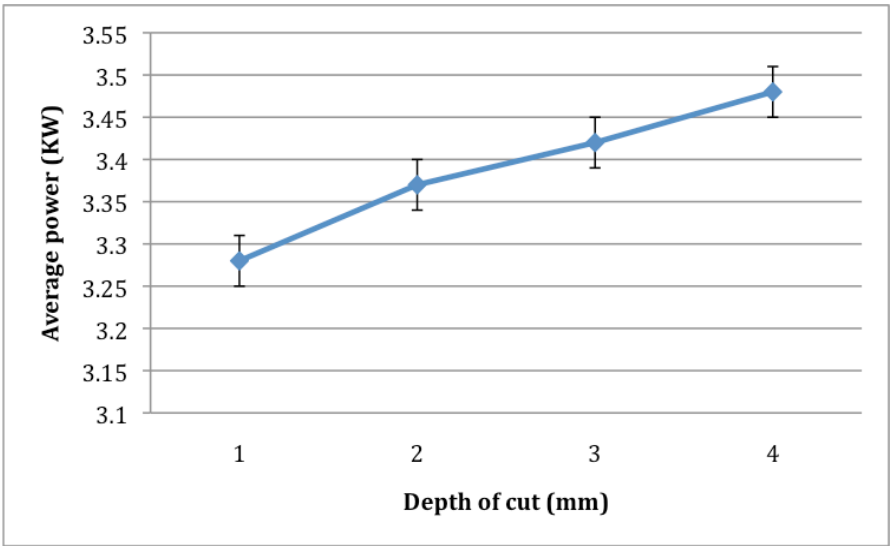

Figure 3: *Average power consumption of the machine for each slot – case of finishing*

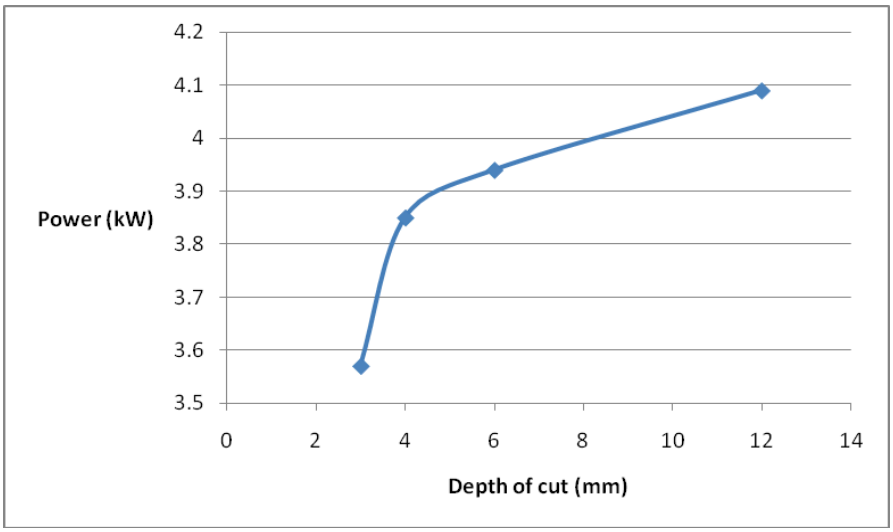

Figure 4: *Average power consumption of the machine for each slot – case of semi finishing*

Figure 5: *Multi-featured part designed for the energy consumption experiment*

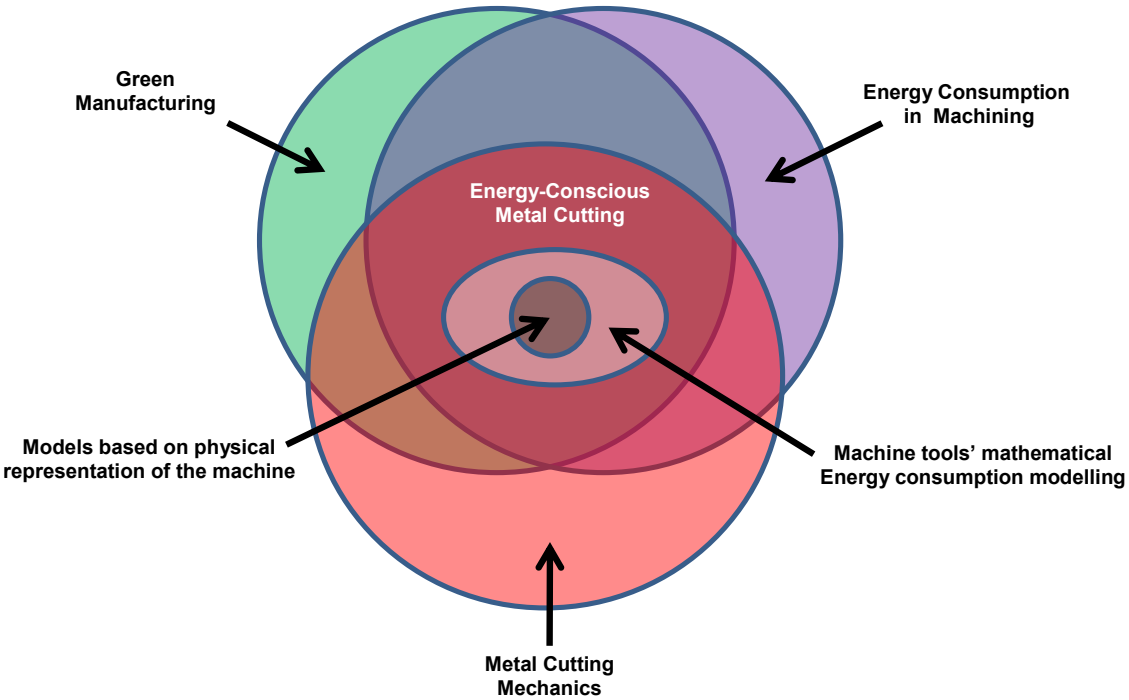

Figure 6: *Schematic view of the fields of research in energy efficiency in machining*