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Energy efficient manufacturing from machine tools to manufacturing systems

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Abstract

Energy efficiency is one of the key drivers for sustainability. Within manufacturing environments, energy efficiency importance has grown, and it is now considered among other decision-making factors such as productivity, cost and flexibility. However, in most cases the energy consumption of the various components of the manufacturing systems, such as machine tools, are considered using average energy consumption models for the needs of discrete event simulation. The paper presents an overview of energy efficiency approaches, focusing in both production and machine tool level and how these two can be integrated together. Furthermore, the main challenges towards energy efficient manufacturing are discussed identifying the major barriers from both technology and cultural point of view.

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1. Introduction

Manufacturing is one of the primary wealth-generating activities. It can be defined as the transformation of materials and information into goods for the satisfaction of human needs. However, turning raw materials into consumer products is also a major source of environmental pollution. This environmental pollution can be the direct outcome of the manufacturing process, or indirectly through the use of energy for running these processes. Manufacturing waste involves a very diverse group of substances, and depends on the technology used, the nature of the raw material processed and the quantity that is discarded at the end of the chain. The large use of energy for industrial operations in Europe (32% of the whole consumed energy) is responsible for significant CO_2 emissions and thus climate change [1].

Over the last decades, the demand for goods has been increased and so has the demand for natural resources and energy. However, the sustainability movement demands the use of more “energy efficient” production methods. In order to achieve this, the manufacturing world has to evolve from "maximum gain from minimum capital" strategy to "maximum gain from minimum resources" [1].

The availability and affordability of energy is becoming a critical parameter affecting the whole life cycle of the product, and subsequently the production phase as well. Manufacturing accounts for more than 30% of the global total energy consumption [2]. According to International Energy Agency (IEA) [3], there is significant potential for further energy and CO_2 savings through the application of proven technologies and best practices. On a global scale adopting such approaches could save between 25 EJ and 37 EJ of energy per year, which represents 18% to 26% of current primary energy use in industry.

However, traditionally the performance of a production system is assessed by monitoring four main classes of manufacturing attributes; namely cost, time, quality and flexibility. Manufacturing efficiency research and development has always focused on technological improvements, however often at the expense of higher energy consumption. These four attributes do not take into consideration energy or resources efficiency that are key to sustainability.

Sustainability has evolved to be a key attribute that has to be considered when making manufacturing decisions. It is evident that manufacturing processes are not optimized with regards their energy consumption, resulting in unnecessary use of energy and resource. Thus, the manufacturing tetrahedron that was proposed by Chryssolouris [4] has to be extended as to include "sustainability" as a new driver in manufacturing.

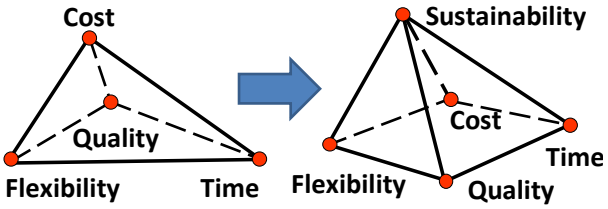

Fig. 1. Manufacturing decision making attributes evolution [5]

Key performance indicators (KPIs) are well established for each one of these manufacturing attributes. "Cost" incorporates a number of factors such as equipment and facility costs, material cost, labour, overhead etc. On the other hand, "time" attribute is monitored using KPIs such as "throughput time", "cycle time", "lead time" etc. In a similar way "quality" is assessed through "surface roughness" measurements, "cost of quality", etc. However, for the case of sustainability, and specifically, energy efficiency, the existing definitions can be rather misleading as indicated by Bunse et al. [6]. In general "energy efficiency" refers to technologies and standard operating procedures that reduce the volume of energy per unit of industrial production. IEA adopted definitions of energy efficiency are: "the goal of efforts to reduce the amount of energy required to provide products and services" and "achieving the same quality and level of some 'end use' of energy with a lower level of energy input".

A number of energy related KPIs have been introduced and can be categorized into metrics focusing in the energy consumption (such as energy consumed per product, total on-site energy, total energy use etc.), environmental impact (CO_2 emissions, greenhouse gas emissions, etc.), financial figures (e.g. energy cost), focusing on the process level, machine tool or production plant etc.

The present paper does not aim to present a thorough state of the art review of energy efficiency in manufacturing systems; this has been recently presented by Duflou et al. [7] in their comprehensive work. The main goal of the present paper is to present an alternative method for addressing the energy efficiency problem that takes into control both the energy demands on machine tool and manufacturing system level. Furthermore, the main challenges towards energy efficient manufacturing are discussed identifying the major barriers from both technology and cultural point of view.

2. Boundaries of Analysis

The energy efficiency analysis can take place on different levels depending on the scope of the project. As indicated by Duflou et al. [7], five different levels were identified: device/process level, line/cell/multi-machine system, facility, multi-factory system and enterprise/ global supply chain. Each one of this analysis levels relies on different assumptions, different input and provides different results. In the present paper, we focus in two more generic levels, the machine tool level (that basically reflects the two first levels proposed by Duflou in a more holistic view) and the manufacturing system level (which can be linked to Duflou's subsequent two levels). The enterprise/global supply chain level is not addressed in the present paper.

3. Energy Efficiency on a Machine Tool Level

A number of recent studies have been published dealing with the energy efficiency of manufacturing processes, however most of these studies relies either solely on the monitoring of the energy consumption of machine tools [8, 9] or on the monitoring of specific machine tools components, such as the spindle [10]. A couple of methods have been proposed such as the "unit process energy" method by Kara and Li [11] and the "energy blocks" method by Weinert et al. [12] that however both rely on energy measurements been conducted in advance.

Few studies have been presented employing modelling tools for assessing the energy consumption of machine tools and manufacturing processes. One example is to model environment as a thermodynamic system, an approach employed by Gutowski et al. [13]. The main challenge for using this approach lies in that it results to a very complex energy problem. This difficulty can be simplified with the use of exergy or "available work". However, the reliability of such approach relies in extensive experimentation.

It has been proven in the past that the energy consumed by machine tools during machining is significantly greater than the theoretical energy required in chip formation. Dahmus and Gutowski [14] showed, for instance, that the specific cutting energy accounts for less than 15% of the total energy consumed by a modern automatic machine tool during machining. Salonitis [5] came to similar figures for the case of grinding.

It is thus obvious that it is essential to accurately measure the energy consumption during the process and cannot solely rely to the theoretical modelling of the process for the estimation of the energy consumption. For the determination of the energy consumption that is caused by the various peripherals of the machine tools, the monitoring procedure has to be designed thoroughly

in advance. Indicatively, for the case of grinding (Fig. 2), it has to be certain that all subsystems are monitored as individually as possible. In most cases these peripherals are consuming the same amount of energy regardless of the process variables. On the other hand, the energy consumption due to process variables has to be also considered during these monitoring experiments.

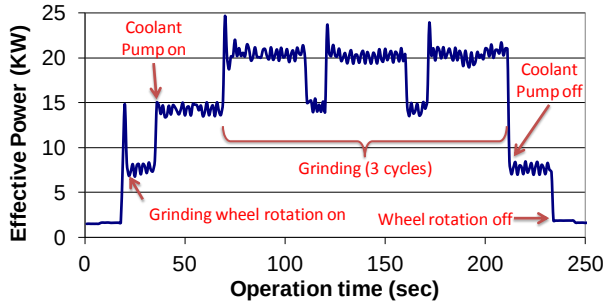

Fig. 2. Energy audit – plunge grinding case [5]

Based on the energy audit of the process, the energy consumption of the machine tool subsystems can be determined (in fig. 3, the energy demand of the various subsystems relative to the process variables consumption is depicted for the case of grinding).

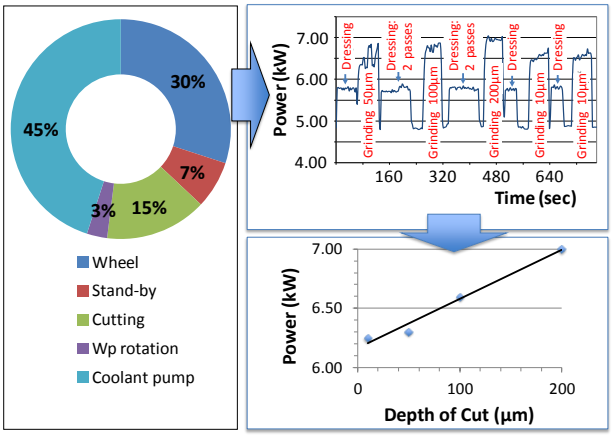

Fig. 3. Cylindrical grinding machine subsystems energy demand [5]

The total energy thus required by a machine tool for performing a specific process can be estimated using the equation:

$$E_{total} = E_{process} + E_{peripherals} \quad (1)$$

where $E_{process}$ is the energy required for the physical process to occur and $E_{peripherals}$ is the additional energy consumed from the machine tool (e.g. for operating the coolant pump, for overcoming the efficiency loses, etc.).

The process energy ($E_{process}$) can be estimated from the specific cutting energy and it depends on the mechanics of the process. Therefore, it depends on the process parameters. Indicatively, in fig. 3, it can be seen that for the case of grinding [5], the process related power fraction depends on the cutting depth. This is in agreement with similar works in other studies. For example this portion of power was correlated with the material removal rate and the energy consumption of turning and milling [11] and grinding [15] was predicted with very good accuracy. An interesting finding is that although this portion of power is not independent of the machine tool used, it is the key main process parameter for material removal process which determines energy consumption.

The machine tool additional energy ($E_{peripherals}$) can be further analyzed to the energy that is a function of the machine load and the energy consumed regardless whether the machine cuts or is idle (background energy) as can be seen in the following equation:

$$E_{peripherals} = E_{background} + E(load) \quad (2)$$

The background energy ($E_{background}$) depends on the specific machine tool used and can be determined experimentally through an energy audit. For the grinding case discussed in the present paper, such background energy includes the coolant pump energy and the stand-by energy (i.e. the energy consumed from the various electronics, the control unit, etc.).

The load dependent energy depends on the specifics of the process. It depends for the case of grinding for example on the workpiece characteristics (weight, material, size), the process parameters selected and the cutting tool used.

This type of analysis is not applicable only to conventional processes such as grinding, turning and milling but can be also used for non-conventional ones. For example Fysikopoulos et al. [16] estimated the energy consumed during laser drilling from the subsystems that are “always-on” and the subsystems that are “periodically-on”.

A common characteristic of almost all manufacturing processes (both conventional and non-conventional ones) is that even when the machine is idle, it is consuming more than 50% of its maximum power. It is thus obvious that there is a lot of potential in energy reductions through better design of machine tools (e.g. sharing of common peripherals between different machine tools in the manufacturing system).

Energy reductions can be also achieved through optimization of the process strategy. Two indicative examples will follow: Salonitis [5] achieved significant energy reductions for the case of grinding through the reduction of process steps and the use of finer grinding wheels and better planning of the dressing operations. Diaz et al. [17] on the other hand, reduced the energy consumption during the milling of pockets through the selection of the optimum tool path.

4. Energy Efficiency on Manufacturing System Level

Energy efficiency within a factory can be tackled at a number of levels, as indicated by Duflou [7]. Improvements at each level will derive benefits and these benefits will be additive. Hence benefits from machine tool level changes can be enhanced by changes at the manufacturing system level. So concentration at only one level will miss opportunities at other levels.

The lean philosophy has delivered significant benefits to manufacturing systems through the focus on flow and subsequent removal of waste. The application of lean has focused on the primary material flow to improve the product delivery to customer. More recently lean tools have been credited with achieving energy savings through direct application or the use of 'lean and green' toolsets [18]. Whilst it may be questioned whether the chief motivation was for economic or environmental improvement, it is clear that energy efficiency gains can be achieved through the manufacturing systems level focus.

The application of lean focuses on the flow between value-adding operations and the removal of waste from non-value adding activities and contrasts with earlier scientific management which focused primarily on the improvement of the value-adding operations. There is an interesting analogy here therefore with energy efficiency in that savings can be achieved through better value-adding activities and technology in isolation as well as considering the activities as part of a wider system flows.

At systems level, savings can come from simple prevention activities such as switching off energy consumers when not in use. Switching off lights when not in use is perhaps an over-used example but the principle extends to the switching off production equipment when not in use. Other savings can come from how equipment is managed when in use, for example, the use of sequencing and batching to maximise the energy efficiency during production periods.

Beyond 'lean and green', there are various research themes within this area. Despeisse et al. [19] have collected practices on the systems level actions that manufacturers have taken. In modelling Solding and Thollander [20] have used discrete event simulation to address energy reduction whilst Ball et al. [21], Hesselbach et al. [22], and Michaloski et al. [23] have using simulation based approaches to integrate buildings and production systems together.

The waste hierarchy (fig. 4) is one means but which manufacturing system level energy efficiency actions can be both classified and prioritised (though others may use TPM structures). The material waste hierarchy [24] is well established and this can be translated into an energy waste hierarchy [25]. An energy hierarchy for manufacturing systems level would include: prevent, reduce, reuse and dispose. Examples of actions arising from such a hierarchy are as follows:

- *Prevention*: switching off equipment at end of shift or powering down clean room air handling when not in use at night.
- *Reduce*: relaxing set points or clustering batches to enable to equipment to run at closer to design load efficiency when in use.
- *Reuse*: harvesting energy from one process for use by another process
- *Dispose*: venting to atmosphere and using the environment as a heat sink rather than using power to cool.

Fig. 4. Waste hierarchy

In more detail, Toyota present six attitudes for use in energy reduction. The first four (eliminate, repair, stop and reduce) are system/behavioural and the latter two (pick up and change) are process/technological [26].

These actions progressively require greater considerations of the operation of machine tools and require technology solutions moving from prevention to dispose activities. However, these can be considered manufacturing system level actions as the machine tool level focus tends to be more on the material transformation rather than wider integration.

The integration from systems level organisation to systems level technical to machine tool level is largely absent from the literature but offers a continuum of benefit that can be progressively exploited.

At systems level complexity (and therefore opportunities from inefficiencies) that come from a combination of the time varying behaviour (dynamics), spatial distances, quantity of energy flow, quality of the energy flow, etc. [27] present challenges in analysis to achieve energy reductions. Simple changes can be judged intuitively but the application of tools such as dynamic simulation (such as discrete event simulation) is need to both assess the impact of changes as well as possibly identify them in the first place [27].

It is notable that the application of simulation tends to be reductionist with systems level simulation lacking the detail of the machine tool and any consideration of the operation of the machine being independent of the wider system. Additionally the disciplines familiar with the different simulation tools tend to exist in different parts of an organisation's structure and performance measurements system do not encourage collation.

One example of where such barriers to analysis are being broken down is where the analysis of the production process does not fall neatly into either machine tool or manufacturing systems domain exclusively. For example, modelling a paint shop involves the high energy consumption parts of the production as well as the production plan of how parts are scheduled into the plant. Improvements can come from changes to air handling as well as to the production sequencing/loading plan.

5. Towards an Energy Efficiency Culture

The implementation of energy reduction initiatives is similar to any other organisational change with many drivers for and barriers to that change. A number of researchers have focused on the barriers to energy reduction. Sorrell et al. [28] categorized these barriers into three major groups: Economic barriers, Behavioural barriers and Organizational barriers (fig. 5).

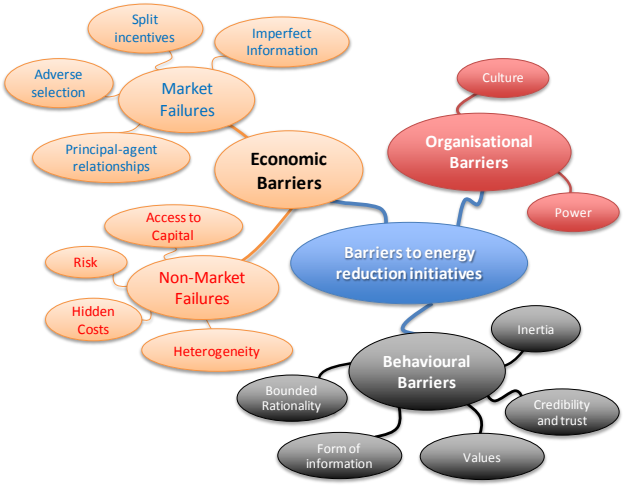

Fig. 5. Barriers to energy reduction

A recent study by Lunt and Ball [29] on the main issues of energy reduction projects/initiatives in an aerospace manufacturer revealed that the key barriers are a lack of accountability (who owns the project) and the lack of understanding regarding energy reduction. The latter can be improved significantly through proper training in order to increase the level of acceptance.

Acceptance depends greatly on human behaviour that can be influenced through campaigns. Human behaviour is a complex area in which many theories have been proposed for explaining what influences and motivates individuals' decisions and choices. To develop effective behavioural change campaigns and ease the transition towards a more sustainable future, consideration of the systemic relationship between individuals' word-views, institutions and technologies must be considered [30]. Thus, an understanding of individuals' worldviews – attitudes, perceptions, behaviours and values – in regard to the adoption of a more sustainable lifestyle is of prime importance.

Within institutions, social and cultural norms are in place to specify acceptable behaviour within the organisational environment [31]. Incorporating sustainability at the core of an organisation's corporate strategy encourages the creation of initiatives to affect day-to-day habits.

Technologies include all tools that are used to enhance social activities, from currency for trading to communication tools for sharing information and so on [30]. Metering and monitoring systems are useful in making energy consumption more visible only if the information is readily conveyed to the various stakeholders. An example of this is the case of Toyota Motor Manufacturing in Kentucky (TMMK) who, after monitoring energy consumption, used a chart covering 25 metres of wall space to convey to employees the organisation's energy objectives. Meetings are held every month to discuss progress in reducing energy consumption. As a result, in 2011 the company met its target, set in 2002, of reducing energy consumption by 29 percent per vehicle [32]. By integrating different communication tools (e.g. posters, interpersonal communication) to promote reduction of energy in institutions, individuals' perceptions and attitudes can be harnessed. Organisations such as TMMK have integrated energy management as a standard, akin to health and safety measures, core to their organisation for continuous improvement.

Overall, the development of campaigns to change individual behaviour involves the consideration of the systemic relationship between individual worldviews, the institution and technologies. The success of such campaigns depends primarily on the ability of the organisation to first assess current energy consumption, develop goals and objectives and finally share them with stakeholders. The development of an integrated and targeted communication campaign at the right frequency of exposure lowers the barriers for change in individual behaviour and encourages the implementation of energy reduction measures and initiatives. Just as standards for health and safety exist to ensure continual improvement, energy management must also be core to the organisation's objectives.

6. Conclusions

Within this paper the energy efficiency from both machine tool, and manufacturing system level is discussed. Improvements at each level will can be multiplied if not considered in isolation. Benefits from machine tool level changes can be enhanced by changes at the manufacturing system level. So concentration at only one level will miss opportunities at other levels.

Furthermore, the main barriers to adopting a more sustainable and energy efficient way in the industrial environment have been presented. It is crucial that for succeeding in introducing energy efficiency measures in any industrial sector, the broad acceptance of such measures must have been achieved in advance from the human resources.

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