Chapter 2
Review on the State of the Research in Energy and Eco-efficiency of Manufacturing Processes

Researches in the field of manufacturing processes traditionally focused on the mechanical performances, such as cutting forces, machinability, surface roughness, dimensional accuracy, etc. The energy consumption and the associated environmental impact of manufacturing processes had been overlooked in the past. Due to the soaring energy price and increasing awareness on environmental impacts, energy and eco-efficiency has become one of the most extensively researched topics in the field of manufacturing. New researches and papers have been published in order to improve the energy and eco-efficiency of manufacturing processes. However, there are few fundamental questions remaining unanswered. For example, "what does energy and eco-efficiency mean to manufacturing processes?", and "how to evaluate them" still remains to be answered. The following sections present the currently available methodologies in the literature that attempt to answer those fundamental questions and define the research gap which still requires to be addressed.

2.1 What Is Energy Efficiency

Energy efficiency now has a frequent appearance in the public domain, which has been discussed intensively in relation to economics, industrial competitiveness, energy security, as well as global warming and climate change (Eichhammer and Mannsbart 1997). In general, energy efficiency refers to the ratio of the useful output of a process to the energy input into a process. Better energy efficiency means using less energy to produce the same amount of useful output. Although it is primarily an engineering term, the definition has already extended to encompass

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economic measures. Patterson (1996) provided a thorough and a critical review of different energy efficiency indicators which can be classified into four main groups:

- Thermodynamic: both of the process output and energy input are derived from the science of thermodynamics.
- Physical-thermodynamic: these are hybrid indicators where the energy input is measured in thermodynamic units, but the output is measured in physical units.
- Economic-thermodynamic: Instead of using physical units, the output is measured by the market price, while the input energy is still in thermodynamic units.
- Economic: Both the energy input and process output are enumerated in monetary terms.

The first two groups are true to the engineering definition of energy efficiency, whereas the economic indicators are generally used in a macro scale for policy making, for instance, the "energy cost: GDP" ratio for a specific industry sector. Since this research focuses on the unit process level, the economic indicators are thus excluded in the further discussions.

2.1.1 Thermodynamic Approach

The thermodynamic indicators are often defined as the science of energy and energy processes, where the heat content or work potentials are measured in terms of thermodynamic terms, such as enthalpy, entropy, exergy and so forth (Patterson 1996). These indicators offer unique and objective measures for a given process in the context of physical conditions, i.e. temperature, pressure, etc. From an enthalpy point of view, the energy efficiency (η) can be defined as Eq. 2.1.

$$\eta_{\Delta H} = \frac{\Delta H_{out}}{\Delta H_{in}} \tag{2.1}$$

where ΔH_{out} refers to the sum of useful energy outputs of a process; ΔH_{in} refers to the sum of all the of the energy inputs into a process.

In the context of industries and manufacturing, the useful energy is generally associated with the minimum energy requirements to perform a task. For instance, Giacone and Mancò (2012) took a glass melting case to demonstrate the calculation procedure of thermodynamic energy efficiency. The useful energy output was computed as the sum of theoretical heat required regarding the temperature changes and chemical reactions of glass melting. However, this thermodynamic approach was only validated on the thermal processes or a furnace. Other machining processes, such as turning, milling and grinding, were initially excluded. For those processes, it is difficult to determine the minimum energy requirement from a thermodynamics perspective, since the temperature changes in the chip-formation areas are extremely sensitive to the combination of workpiece material, tool geometry, cutting parameters and other process conditions (O'Sullivan and

Cotterell 2001). One alternative is to use cutting forces to estimate the minimal energy requirement of a machining process, as shown in Eqs. 2.2 and 2.3.

$$P_t = F_c \times V \tag{2.2}$$

$$\mathrm{E} = \int_{t_1}^{t_2} P_t \cdot d_t \tag{2.3}$$

where P_t refers to the instantaneous power; F_c refers to the cutting force; V refers to the cutting speed; E refers to the energy consumption from time t_1 to t_2.

There were different theories and approaches for cutting force prediction, such as orthogonal machining theory, empirical modelling, finite element method, etc. As cutting force prediction is not the main research objective, a few leading researches about this topic have been reviewed.

Oxley's model is one of the widely accepted theories of cutting force prediction. He has investigated the mechanics of machining based on a geometrical model of chip formation (Oxley 1998). This model is very useful for predicting cutting forces, tool life as well as optimizing cutting conditions. However, this model still had several major limitations. One of them is that the model was limited to plain carbon steel work materials. To extend this approach, as Oxley suggested, the high strain-rate/high temperature flow stress of other materials in appropriate machining conditions should be developed. Another limitation of this model is that it assumed a plane cutting face tool, whereas many industrial tools have chip breaking devices such as obstructions located on the tool's face. Also, the model assumed that the cutting edge keeps perfectly sharp during the machining process. Lee has extended Oxley's machining theory in 2007 (Lee 2007). The author conducted a series of experiments to verify the methodology under various cutting conditions such as cutting speed, feed, tool nose radius, material hardness etc. Lee introduced the magnitude of tool radius into this model, which improved the model by not assuming that the cutting edge is perfectly sharp. Johnson-Cook's flow stress model also has been included in the model in order to extend the range of Oxley's model. However, Lee only experimentally validated this approach on hardened alloy steel. In 2009, Liu et al. presented a similar work, who also introduced Johnson-Cook's flow stress model into Oxley's model (Liu et al. 2009). They validated the methodology only on aluminum alloy work pieces.

Armarego is another leading researcher in the field of cutting force modelling for turning and milling processes. Different cutting force models have been published through the use of both theoretical and empirical approach. The theoretical investigation was initially conducted to analyze two oblique cutting processes (Armarego and Wiriyacosol 1978). The model has suggested the existence of a common oblique cutting theory, which has formed the fundamental tool for further researches on cutting force modelling. Different models have been published for turning and milling processes (Whitfield and Armarego 1986; Budak et al. 1996; Armarego and Samaranayake 1999). Although the cutting force models showed a high accuracy of predicting cutting forces, the models were only validated for a specific case. Critically, the consistency among those cutting force models was lacking. The empirical modelling approach was also used in some of the researches (Armarego et al. 2000). In that paper, a large amount of available database and empirical models has been reviewed since Taylor's work in 1907. Some attempts to optimize the cutting force, surface roughness and tool life have been documented in Armarego and Brown's (1969) seminal book. Although the existing equations have covered a wide range of process conditions, the values of exponents and constants in the empirical equations were found unreliable.

Other researchers have also provided different types of cutting force models (Kline et al. 1982; Stephensen 1989; Axinte 2001). The models have all claimed achieving a great accuracy, but the uncertainty of the cutting forces has been also stated.

For a more complex machining process, like grinding, the cutting force prediction is more problematic. For instance, grinding force consists of three stages, ploughing, cutting and rubbing. Each one of them has resulted in a complicated model (Li and Fu 1980; Liu et al. 2008; Doman et al. 2009; Durgumahanti et al. 2010). Thus the estimations of minimum energy requirement based on cutting forces are not as applicable as they may first appear.

Another alternative for estimating the minimal energy consumption is to use the specific cutting energy or specific grinding energy for material removal processes. Kalpakjian and Schmid have included a table of specific cutting energy for different materials in their book (Kalpakjian and Schmid 2005). The recommended value for steel ranged from 2.7 to 9.3 $\text{w} \cdot \text{s/mm}^3$. However, how to determine the specific energy was not presented. Malkin and Joseph (1975) presented a more detailed work for grinding process, plotting specific grinding energy against the specific material removal rate. However, the exponent and constant were still missing for an applicable estimation. He also suggested an average enthalpy increase between ambient temperature and liquid state as 10.5 kJ/cm^3 for iron and steels (Malkin and Guo 2008). Despite the approximation, the value tested was over-estimated since the material does not all melt completely. Besides the academic researches, the tool suppliers also provide some useful information for specific cutting force estimation. SECO® tools, a major turning and milling insert supplier, has included a specific cutting force (k_c) calculation in its catalogue, as Eq. 2.4 (SECO® 2009).

$$k_c = \frac{1 - 0.01\gamma_0}{(f \sin\alpha)^{mc}} k_{c1.1} \tag{2.4}$$

where f refers to the feed rete; α refers to the approach angle; γ_0 refers to the rake angle; mc refers to material exponent; $k_{c1.1}$ refers to the shear stress of the workpiece material. A complete dataset of exponents and constants for different cutting tools and workpiece material can be found in the catalogue, which makes the specific cutting energy estimation most applicable. However, it can be only applied to turning and milling processes.

Despite the sophisticated calculation of minimal energy consumption, the definition of useful energy output has been criticized by different authors due to the implicit value judgment (Boulding 1981; Patterson 1996). For instance, the turning process also requires energy for spindle rotation; if only the cutting energy is considered as useful output, all the other energy requirements are considered as waste heat, resulting in a biased estimation of energy efficiency.

In addition, another problem with the enthalpy energy efficiency is that it does not consider the energy quality of the inputs and the useful outputs (Patterson 1996). However, this problem becomes significant when applying to a complex system where a mix of energy resources is used. For instance, the majority of manufacturing processes require electricity as energy input, but the electricity generation and the material processing consume various natural resources. To overcome the problem, the thermodynamic quality measures are introduced, such as exergy. The definition of exergy is, "*the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes involving interaction only with the above mentioned components of nature*" (Szargut et al. 1988). Gutowski et al. has used this concept to provide a platform to evaluate the environmental impacts among material preparation phases to manufacturing process, as shown in Fig. 2.1. The methodology was adapted from several thermodynamics books (Szargut et al. 1988; Smith et al. 2001; Gyftopoulos and Beretta 2005). As the Fig. 2.1 shows, there are three important aspects of manufacturing processes: (1) the energy requirements for the materials; (2) the energy requirements for manufacturing processes themselves; and (3) the efficiency of the material and exergy transformations in manufacturing processes. The definition of energy, enthalpy, entropy, heat, work, temperature and exergy can be

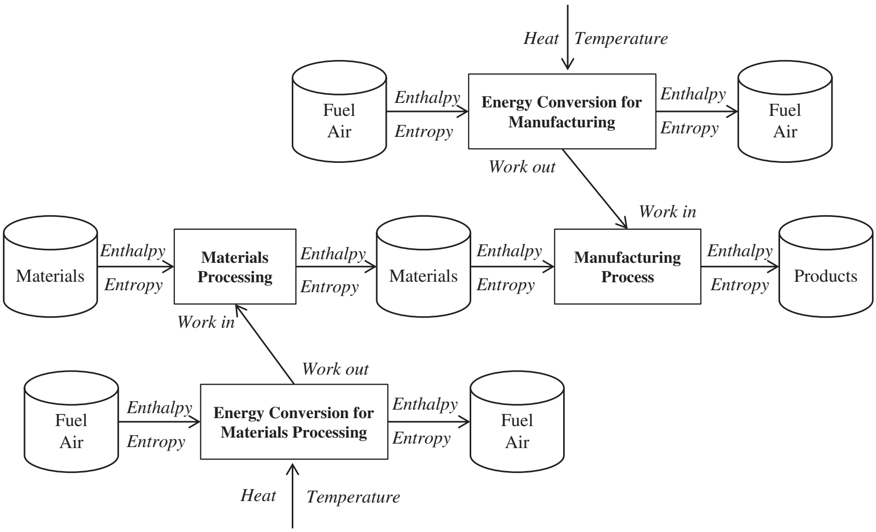

Fig. 2.1 Overview of the thermodynamics of manufacturing processes (Gutowski et al. 2007)

found in aforementioned books. Although the framework provides little information about energy efficiency of manufacturing processes themselves, it is still valuable to have the overall picture of the entire production stage. As Gutowski et al. suggested, once providing a reliable prediction of the energy consumption of manufacturing processes, the environmental impact of the entire manufacturing industry will then be obtained in conjunction with the energy efficiency of material processing.

2.1.2 Physical-Thermodynamic Approach

Besides the challenges of determining the useful output in terms of either heat content or work potential, the thermodynamic measurement does not reflect the end use service required by consumers. Hence, the efficiency ratios measure the output in physical units rather than in thermodynamic terms, whereas the input energy is still measured in traditional thermal terms, such as joule. For instance, the function of a general turning process is to remove material to achieve a round profile. This output can therefore be measured by cm^3.

As suggested by Patterson, one advantage of using physical measures is that they can be objectively measured as thermodynamic measures can, meanwhile they have the added advantage that they directly reflect what consumers are actually requiring in terms of an end use service. Furthermore, the market value of the output can be further converted from the physical measures, which enables longitudinal analyses (Patterson 1996). Therefore, these hybrid physical-thermodynamic measures of energy are widely used in industrial, residential, commercial and other sectors.

Obviously, the energy intensity indicator, which is the input energy consumption per part or a unit service, is the inverse of the physical-thermodynamic measures of energy efficiency. It is also called as specific energy consumption, SEC, as shown in Eq. 2.5. The use of energy intensity or SEC can be found in numerous industrial cases. For instance, Phylipsen et al. defined the energy efficiency indicators for the iron and steel, aluminum, cement, and other energy intensive industries. The specific energy consumption was selected to compare among different countries and industries (Phylipsen et al. 1997). Tanaka compared different energy efficiency measurements, such as absolute energy consumption, energy intensity and thermal efficiency. The specific energy consumption was finally selected for the case of iron and steel industry in Japan (Tanaka 2008).

$$SEC = \frac{Energy\ input\ into\ a\ process}{Physical\ output\ of\ a\ process} \quad (2.5)$$

For a unit manufacturing process, the specific energy consumption is more favorable than other energy efficiency indicators. The aforementioned specific cutting energy or specific grinding energy is actually the form of energy intensity measures. Notably, these indicators only refer to the minimum energy requirement, which is completely different from the specific energy consumption of a unit process. In other words, the energy consumptions of auxiliary components need to be taken into account. In that sense, the total energy consumption of a machine tool needs to be measured in addition to the cutting energy or the spindle energy demand.

More importantly, the specific energy consumption is not constant for a unit manufacturing process. Owing to its dynamic nature, the specific energy consumption varies according to different process parameters, workpiece materials. For example, Eq. 2.4 has already shown the dynamics of specific cutting force, which directly affects the loads on the machine spindle as well as the total energy input into the process. Therefore, a model is required to characterize the relationship between the specific energy consumptions and process parameters. Ideally, the model should offer a reliable prediction of specific energy consumption for a given process, which will enable further environmental analysis and development of energy efficiency strategies.

2.1.3 The Predictions of SEC

Prior to this research, the prediction of SEC for unit manufacturing process remains unreliable or inapplicable. The existing models or methodologies fail to cope with the total energy consumption of a machine tool, or the dynamic behaviors of the energy consumption, as reviewed below.

One attempt is to link the minimal cutting energy requirement with the total energy consumption of a machine tool, which primarily assumes that the minimal cutting energy is predictable. In other words, the machine or motor efficiency (η) is targeted for modelling. However, no existing work has been conducted at machine tool level. Draganescu et al. (2003) attempted to model the spindle motor efficiency on a vertical milling machine. The motor efficiency has been defined as Eq. 2.6, where P_c refers to the minimal cutting power; P_{mc} refers to the consumed power by the spindle drive motor.

$$\eta = \frac{P_c}{P_{mc}} \tag{2.6}$$

The authors used the response surface methodology to establish the relationship between the machine tool efficiency and working parameters such as spindle speed (n) and torque (M_t). The derived model for the tested milling machine is shown in Eq. 2.7; and the efficiency surface response is shown in Fig. 2.2.

$$\begin{aligned}\eta = \exp\Big[&-9.136 + 2.362\ln n + 1.135\ln M_t - 0.166(\ln n)^2\\ &- 0.141(\ln M_t)^2\\ &- 0.083(\ln n)(\ln M_t)\Big]\end{aligned} \tag{2.7}$$

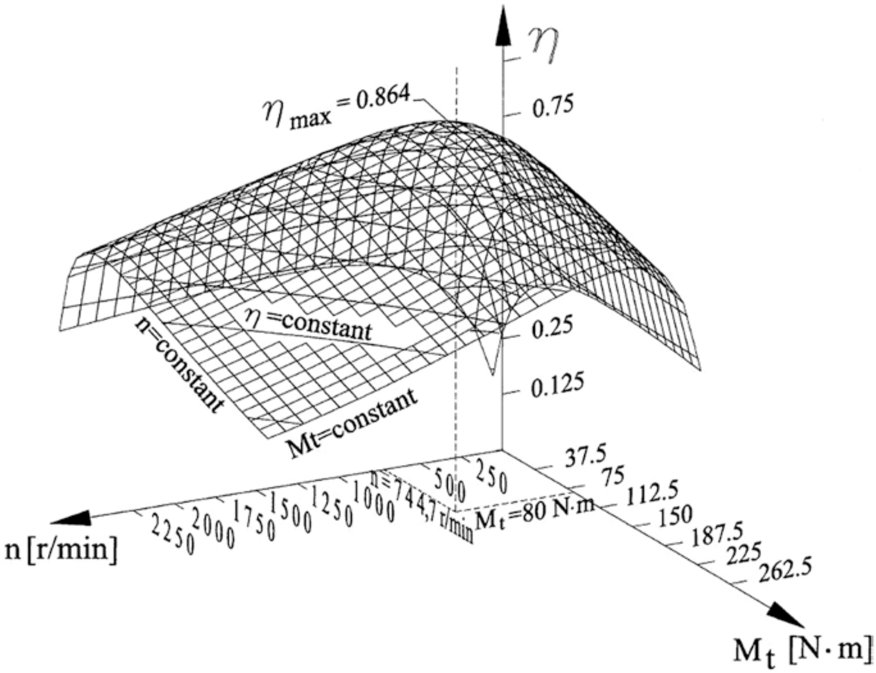

Fig. 2.2 The efficiency surface response for a tested spindle motor of a machine tool (Draganescu et al. 2003)

As the model suggests, the efficiency of the spindle motor has shown a complex trend against the load on the machine tool. However, the derived empirical model for motor efficiency is unlikely to be applied for specific energy consumption of the machine tool. Moreover, this statistical analysis was limited to one specific machine when operating on aluminum alloy. The reliability of the efficiency model cannot be guaranteed with other machines or processes.

On the contrary, disregarding the machine efficiency would result in failure of the prediction of energy consumption. Klocke et al. (2010) has presented a theoretical calculation of the cutting power. The total energy consumption of the machine tool was assumed as the sum of idle power and cutting power. However, the prediction has failed to match the measured energy consumption. The reason was mainly due to the exclusion of waste energy (e.g. heat) during the metal removing period. In other words, the energy consumption of a machine tool is not just fixed power plus working power. The internal energy conversions and transmissions remains as a complex manner, yet unknown.

Other researchers consider the dynamics of machine tools as the different states from power on to off, such as start-up, stand-by, ramp-up, processing, ramp-down, and power-off. Dietmair and Verl (2008) accomplished a case study of energy consumption forecasting based on the measurement of a machine tool at different states. Figure 2.3 shows the machine states over a measuring cycle.

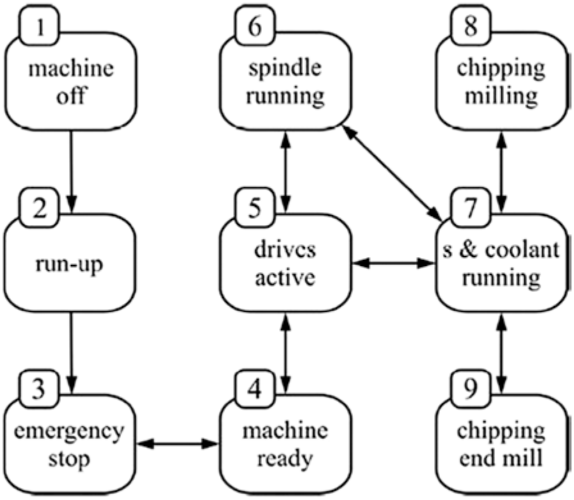

Fig. 2.3 Operational states and the measuring steps (Dietmair and Verl 2008)

This approach is very helpful to allocate the energy consumption of each component, which does not require direct measurement at the component level. Alternatively, the power change between operational states was associated with activated or deactivated components. The authors also claimed the ability to forecast the energy consumption of milling a sample piece. However, the process parameters during the milling process were kept constant throughout the research. In other words, the method was incapable of handling the dynamics of the removal loads.

The initiative—Cooperative Effort on Process Emissions in Manufacturing (CO_2PE!) has been launched by a worldwide collaboration of universities, aiming to document and analyze the environmental impact for available manufacturing processes (Duflou et al. 2010). Since the electricity consumption of unit process is the main contributor of induced environmental impacts, the electricity consumption has been the focus in this initiative. A screening approach was proposed which was similar to the Dietmair's state-based description of machine tools. The power consumption of the machine tool was recorded under different states such as ramp up, standby, processing, ramp-down, etc. However, the energy consumption regarding the change of process load has not been modelled. Therefore, the results cannot respond to the dynamic process load.

Since most of manufacturing processes mainly consume electricity, the exergy concept has been adapted to assess the electricity requirements of manufacturing processes (Gutowski et al. 2009). The energy consumption of the machine tools were simply separated into two parts, one for actual machining, one for other activities such as work handling, lubrication, tool changing, etc. This relationship was expressed as Eq. 2.8.

$$P = P_0 + k\dot{m} \quad (2.8)$$

where, P refers to the total power demand of the machine tool; P_0 refers to the idle power; $\dot{m}$ refers to the process rate (mass/s); and, k is a constant (J/mass). The equation can be converted into a form of specific electricity consumptions (B_{ele}) as Eq. 2.9.

$$B_{ele} = \frac{P}{\dot{m}} = \frac{P_0}{\dot{m}} + k \quad (2.9)$$

However, the definition of the involved factors remains uncertain, for instance, how to determine the constant k, which consists of the idle power. Moreover, there was no experimental evidence to prove this exergy relationship. The estimation of specific energy consumption also requires accurate value of each factor, such as idle power and the constant for specific machines and processes. Without being given the values and clear definitions, the prediction of specific energy consumption for manufacturing processes remains infeasible.

Instead of using experimental data, the specific energy consumptions from subtractive processes, to net shape processes have been calculated based on rough estimation and averaged data. Gutowski et al. (2005) then collapsed all the specific energy requirements into one single chart (see Fig. 2.4). This figure has mainly used to address the increasing trend of energy intensity for advanced manufacturing processes. For instance, oxidation, EDM and sputtering sit in the upper left end of the trend, where as conventional machining and injection molding process were located at the lower right end. In addition, the authors used the exergy equation (Eq. 2.9) to describe trend. However, there is little information about the specific k or P_0 values found in the paper. Therefore, the prediction of unit process energy consumption was still not applicable.

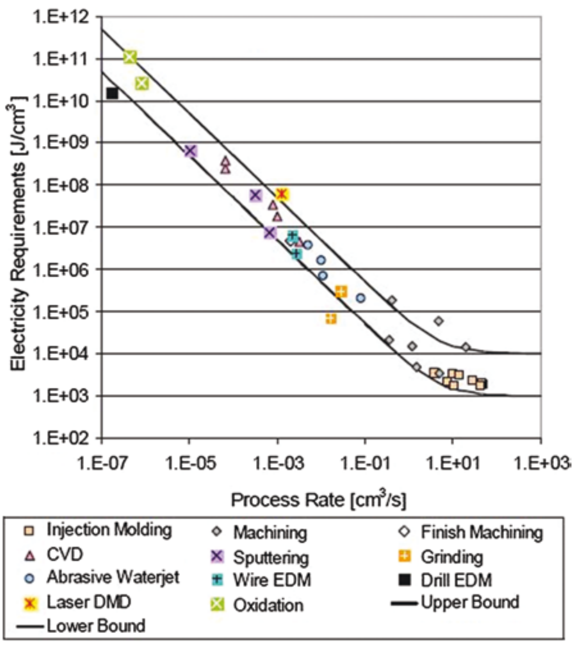

Fig. 2.4 Specific energy requirements for various manufacturing processes (Gutowski et al. 2005)

Renaldi et al. have continued to define the exergy efficiency of manufacturing processes (2011). The authors have compared different definitions for a variety of manufacturing processes. However, the definition for a specific case was still found unclear. Therefore, the exergy concept and framework still remain at a theoretical level, which is not suitable for evaluating and predicting specific energy consumption of manufacturing processes.

In summary, the aforementioned studies do not provide a reliable methodology to estimate and predict specific energy consumption of a unit process, thus calling for the need for such ability that will be developed in this research.

2.1.4 Energy Efficiency Practices in Manufacturing

The energy efficiency is not just an indicator. The definition given by World Energy Council (WEC) suggests that "*Energy efficiency improvements refer to a reduction in the energy used for a given service (heating, lighting, etc.) or level of activity*" (WEC 2008). The understanding of energy efficiency has evolved from a simple input/output ratio towards the global efforts for energy reduction. The researches and practices in the field of manufacturing have been conducted in the different levels from component, to unit process, and factory level.

At the component level, the researches of machine tools have also showed great efforts to improve the energy efficiency. Abele et al. (2010) has reviewed the state-of-the-art technologies and researches for machine tool main spindle units. Normally, the spindle unit is the biggest energy consumer in the machine tool. Different models and simulation tools have been developed for improving the design of spindle motor. However, the focus still remained on the quality performance of the spindle unit, such as accuracy and reliability. There also exist plenty of mechanical design solutions and drive methods to achieve a high-speed production but not compromising any other quality indicators. Mori et al. (2011) has given a perspective from machine tool builder side. A new acceleration control method was developed to reduce the time for non-value adding activities, such as tool change, positioning, acceleration, returning, etc.

At the unit process level, Munoz and Sheng (1995) has proposed an analytical approach to evaluate the environmental impact of machining processes by considering process mechanics, wear characteristics and lubricant flows. Although the tool wear and the efficiency of applying cutting fluid can be improved, the gap towards environmentally-conscious manufacturing remains large due to the exclusion of energy consumptions. In addition, isolating the process from the machine tool cannot provide the true efficiency of any manufacturing processes. Anderberg et al. (2009) has developed a cost model to evaluate both cost and energy efficiency of a CNC lathe machine. The proposed model covered multiple types of cost, such as energy cost, machine cost, tool cost, operational cost, carbon dioxide emission cost, etc. Although the direct energy cost was not comparable with direct machining cost (tool cost and labor cost), the high energy consumption did reflect the least cost-efficient alternative. The author also suggested a better knowledge about the relationship between important machining parameters and energy consumption will increase the energy efficiency for the CNC machining processes.

At the factory level, simulation has been used to characterize the energy and material flow within the factory. Thiede and Herrmann (2010) presented a holistic view of simulating a manufacturing system considering the interrelationship among processes and the technical building services. But the dynamic behavior of individual process was not modelled. The energy efficiency improvements would be more useful if the unit energy consumption model can be integrated within the simulation system.

Besides the above mentioned energy efficiency practices, Herrmann et al. (2009) provided an extended perspective. They have strategically pointed out the limitation of solely improving energy efficiency. According to their suggestions, all the relevant input and output flows should be considered, including heat, compressed air, coolant, periphery system, etc. In other words, all the consumed energy and resources need to be considered to avoid shifting the problem shifting as well as to enable the overall efficiency of a machine tool. This suggestion leads to the discussion of the second keyword of this research, eco-efficiency.

2.2 What Is Eco-efficiency?

2.2.1 The General Definition of Eco-efficiency

The original meaning of eco-efficiency is defined by World Business Council for Sustainable Development (WBCSD):

> Eco-efficiency is achieved by the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the earth's estimated carrying capacity. (WBCSD 2000)

The eco-efficiency is generally measured by Eq. 2.10 (WBCSD 2000):

$$\text{Eco-efficiency} = \frac{\text{Product or Service Value}}{\text{Environmental Impact}} \tag{2.10}$$

The numerator in the ratio is normally indicated by either quantity of product produced/sold or net sales of a business, while the denominator considers energy consumption, water consumption, material consumption, greenhouse gas (GHG) emissions as well as ozone depleting substance (ODS) emissions (WBCSD 2000).

This concept was primarily applied to evaluate the profitability and environmental responsibility of a corporation or a product throughout its life cycle (Sinkin et al. 2008; Aoe 2007). Strategies for improving eco-efficiency have then been proposed accordingly. However, the main interests of manufacturers are the activities within the factory or during manufacturing stage. In fact, the operations as well as the improvement measures are mostly executed at unit process level.

Thus, the concept of eco-efficiency should be applicable for unit processes and transferable among different processes to magnify the benefits at corporate level or throughout product life cycle.

Gutowski (2010) has initially discussed eco-efficiency for unit manufacturing process, where he recommended that eco-efficiency is often the reciprocal of some intensity metric, e.g. energy intensity. It is true for those processes whose energy consumption dominates their environmental impacts. However, this perspective should be extended by considering processes and materials which are needed to support the actual value creation process, because these supporting materials (e.g. coolant) and supporting processes (e.g. coolant filter) have significant environmental impacts. Therefore, a more holistic view of evaluating eco-efficiency for unit process is necessary, but still remains absent.

2.2.2 Environmental Studies of Manufacturing Processes

One of the differences between energy efficiency and eco-efficiency is the consideration of environmental impacts of the unit process. A series of environmental analysis has been conducted among different manufacturing processes. Since the environmental impact of the most tested process is mainly due to the electricity usage, those environmental analyses all started with energy consumption studies. Essentially, there is no difference between energy efficiency and eco-efficiency at this point.

Kordonowy (2002) experimentally measured the energy consumption of selected machines for his B.Sc. thesis. In his thesis, the energy consumed by a machine could be broken down to three stages, such as constant start up stage, constant operation stage, machining stage. A similar state-based measurement was conducted to assign energy consumptions for each machine component. Kordonowy further measured the machining power when applying different material removal rates to the machines. According to the results, the machining power consumption varies dramatically due to different material removal rates. But Kordonowy did not explain how the process parameters impact on the energy consumption. Instead of establishing the relationship between energy consumption and process parameters, the research focused on the constant parts, and tried to theoretically calculate the idle power consumption by using the machine specifications. However, this estimation was unsuccessful especially when applied to the lathe machine (calculated 21810 W vs. measured 1770 W).

Nevertheless, Kordonowy's thesis had provided some useful information for further rough analysis. By referring Kordonowy's findings, Dahmus and Gutowski (2004) then presented a system level environmental analysis of machining processes where grinding process was excluded. In this paper, the authors stated that the energy necessary to actually cut the material is only an insignificant fraction of the total energy consumption, and the differences between different cutting conditions were ignored when attempting to assess the total system energy requirement.

Those statements were based on the previous research of Toyota production processes by Gutowski et al. (2005). By creating an annual production scenario, the actually machining energy consumption was assumed to be only 14.8 % of the total energy consumption. However, this analysis was embodied in the entire production line for a long period of time. The fraction of machining energy consumption was dependent on how many vehicles were produced during that time. Thus, it is unacceptable to ignore the impact of machining parameters on total energy consumption in a smaller scale of production or in unit process analysis. Later, the roughly estimated energy consumption for material removal has then been compared with other energy requirement such as material production, cutting fluid preparation, tool preparation, tool construction and others. The results showed that the embodied energy in the material dominate the energy involved in the material removal processes. However, the energy requirement during the material production does not belong to the unit process, as the material is not created or consumed by the process itself. Therefore, the involvement of embodied energy of raw material can result in a biased conclusion of environmental impacts of unit process.

In 2006, Thiriez and Gutowski conducted series of power measurements on three types of injection molding machines: hydraulic, hybrid and all-electric machines. A similar procedure was conducted to allocate energy consumption to each component. In addition, Thiriez (2006) attempted to model the relationship between energy consumption and throughput rate in his thesis. However, the results were quite poor. The derived regression models showed low R-square values for the tested machine tools (less than 0.5); and, the models did not agree with the proposed exergy framework (Eqs. 2.8 and 2.9).

In that research, besides the basic energy consumption analysis, the life cycle inventory analysis of injection molding process was also included. It has identified that the major contributor for the environmental impacts is due to raw material production. Similar to the results of material removal processes, the embodied energy in the raw material has overweighed the energy consumption during other stages. But this does not mean that the energy consumption during manufacturing stage can be neglected. On the contrary, the manufacturing stage is more dynamic than material production; and the total energy consumption due to manufacturing is still considerable. Hence, the improvement of energy consumption and environmental impacts of unit manufacturing processes is still demanded.

Overall, the above mentioned environmental analysis only considered an average specific energy consumption of a unit process, which resulted in constant results of environmental impact of tested process. Consequently, the process dynamics have been excluded in the current studies. More importantly, the energy for material production was incorrectly included in the analysis of unit process. From the unit process point of view, the material is only changed in its geometric, surface and other features from raw material to end product. The material amount is not created from zero to certain gram for an injection molding process; or, the chips do not disappear for a turning or milling processes. Therefore, the embodied energy for a material should be considered from a product point of view, not unit process; and the environmental impacts during material production stage need to be studied separately.

2.2.3 LCC/LCA Approach

Calculating eco-efficiency based on a ratio between life cycle costs and life cycle assessment (LCC/LCA) is proposed by different authors (Kicherer et al. 2007; Huppes and Ishikawa 2005; Lyrstedt 2005).

According to Westkämper et al., LCA is a technique to assess environmental impacts associated with a function. Generally, it is applied to a product, but the product is defined as an object to fulfil a certain function. A holistic view is essential for LCA, which should cover the entire life cycle of the product or the function, as well as different types of environmental impacts. The LCC refers to the valuation of the costs of production, installation, usage and disposal (Westkämper et al. 2000). By assuming that life cycle cost reflects the value of the product or a function, the LCC/LCA can theoretically provide the information for its eco-efficiency (Lyrstedt 2005; Kicherer et al. 2007). However, the proposed cases were originally for the assessment of a product or company in order to support decision making. Huppes and Ishikawa (2005) provided a theoretical approach for assessing eco-efficiency of society. To adapt this LCC/LCA method for unit process, the information about every involved life cycle activities need to be provided. Taking grinding process as an example, besides the electricity consumption, the resources consumptions such as coolant, the grinding wheel also should be included in the eco-efficiency analysis. In that sense, the cost and the environmental impacts of producing and consuming those resources need to be estimated. However, none of the information can be found in either previous literature or Life Cycle Inventory (LCI) databases. In order to gather above information, it needs a joint effort from machine tool builders, cutting tool suppliers, coolant makers and the users.

In short, due to the high demand of input information, the LCC/LCA is inapplicable for the case of unit process at the moment. Therefore, the methodology of evaluating the eco-efficiency of unit process is required in this research.

2.3 Ensuing Need for Research

This chapter has mainly reviewed the existing methods for characterizing energy and eco-efficiency of unit manufacturing processes. The indicator for evaluating energy efficiency has been selected, and the specific energy consumption is favored due to the objective measurements, as well as the meaningful reflection of customer requirements. However, the current methodology faces shortages to either describe or predict the dynamic behavior of unit manufacturing processes. Therefore, there is an essential need to develop unit energy consumption models to characterize the relationship between specific energy consumption and process parameters, in order to evaluate the energy efficiency of a unit process.

The eco-efficiency for unit process is also under development. Although the eco-efficiency can be simplified as the reciprocal of energy intensity for processes that only consume electricity, other resource consumptions need to be taken into account for a relatively complex process, such as grinding. In addition, the process value remains undefined for the case of unit process. Therefore, the methodology of characterizing eco-efficiency for unit process also needs a systematic development.

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