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A FRAMEWORK OF AN ENERGY-INFORMED MACHINING SYSTEM

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ABSTRACT

Sustainable manufacturing is regarded as an essential criterion to advance competiveness of manufacturing enterprises. Energy consumption or energy efficiency of a manufacturing system is one of the key sustainable performance indicators. Monitoring of a manufacturing system requires inclusion of energy information, e.g. total consumption recording and detailed energy-flow tracking in the entire system. Analysis of the gathered energy information in connection with other applications, such as machining parameter optimization, is a necessary step towards energy-informed manufacturing. Based on literature review, a framework of an Energy-informed Machining System (EiMS) is proposed. Machining processes, such as milling, turning, drilling, grinding, are the scope of this research. With a true energy consumption picture, a more efficient, competitive and environmental-conscious production can be achieved. In order to integrate energy information into the CAx chain, STEP/STEP-NC standards are used as the data representation and exchange protocol, giving manufacturing system an intelligent and interoperable nature.

KEYWORDS

Energy consumption, Sustainable machining, STEP/STEP-NC, Optimization

1. INTRODUCTION

Manufacturing as a main sector of value creation has played an important role in most industrialized country for a long time. Three goals i.e. time, cost, and quality are widely accepted and pursued by enterprises. Finding the optimized trade-offs among these goals attracts a great amount of research and development activities in this area. Moving into the 21st century, environmental issues or crisis are looming large, which forced the manufacturers to take issues of sustainability into account, if not shifting focus from profit to environmental awareness. Companies started to realize sustainable manufacturing is not just law-abiding behaviour, but a great opportunity to increase their competitiveness in the global market (Romvall et al. 2010). Thus, the three goals need to be reconsidered and harmonized under the perspective of sustainability.

These days, more than 70% of manufacturing businesses in the UK and the US rely on the CNC (Computerized Numerical Control) machines (Swamidas and Winch 2003). In most developing countries, such as China, the use of CNC machines is increasing rapidly. While taking the advantage of the high efficiency, accuracy, productivity brought by CNC machines, effective and continuous monitoring and control of the automatic machine is also demanded to ensure safety and stability.

CNC machining as one of the fundamental manufacturing technologies consumes a significant amount of energy. To understand the machining, which is usually regarded as material removal process, under sustainability scenarios, it is necessary to analyze the system from the energy point of view. In this research, machining process is reconsidered as an energy utilization process. Conventional machining operations, such as turning, milling, boring, grinding etc., are considered. In Section 2, literature in sustainable manufacturing area is reviewed, based on which a framework of an energy-informed machining system is presented in Section 3. Energy-informed machining parameters optimization is stated in Section 4, as an example to integrate energy data. The STEP-NC based data modal is then proposed for machining parameters optimization in Section 5. In Section 6, discussion and future work is presented.

2. LITERATURE REVIEW

2.1. ENERGY CONSUMPTION IN MACHINING

Having a clear and comprehensive view of energy flow within a production process is the basis to perform any energy efficiency research. In a machining process, different types of machine tools and auxiliary devices are the basic functional elements. Industrial motors as a major energy source received a remarkable research attention, a total energy breakdown is presented in a review by R. Saidur (2010). More than one component, such as motor, pump etc., consumes energy (Figure-1). Only 15% of the total energy is consumed by actual cutting component (Gutowski et al. 2005). More than 55% of the total energy is consumed in coolant and oil supply. An early work by Byrne and Scholta (1993) pointed out that the cutting fluids were also the main source of pollution, and it was evident that the conventional approach to develop manufacturing processes seriously limited the sustainability improvement.

However, to reduce energy consumption is not simply to reduce the use of cutting fluids. This is because the reduction of cutting fluids will result in more energy consumption during machining (Weinert et al. 2004), and will induce tool degradation and thermal transformation (Popke et al. 1999).

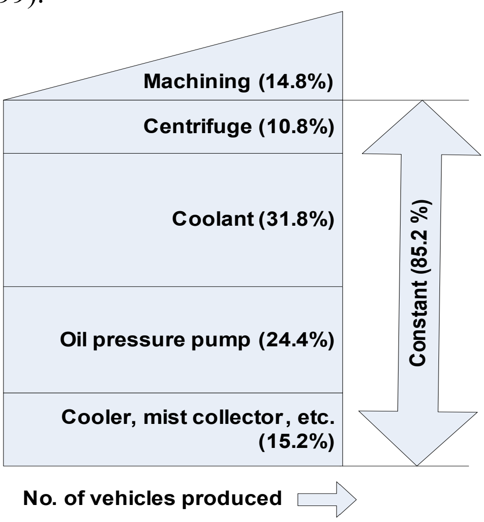

Figure 1 – Energy use breakdown for machining (Gutowski et al. 2005)

Besides, in another point of view, research on energy consumption in different machining states found out that actual cutting process only takes a small percentage of total energy. Figure-2 shows that only 25% of the input power is consumed by actual processing, while 45% is consumed in idle state or losses (Dietmair and Verl 2008; 2009). Anderberg et al. (2010) estimated the ratio in a cost manner, indicating setup cost 31.3%, idle cost 26.1% and direct machining cost 38.7%.

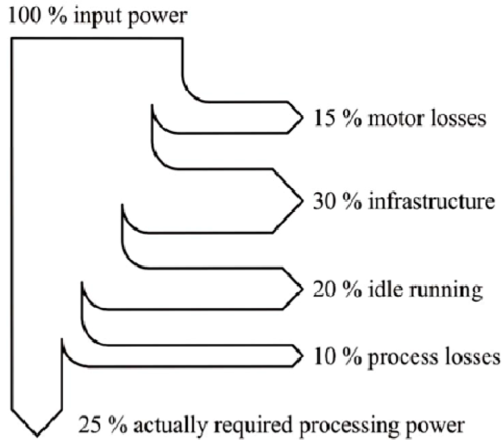

Figure 2 – A Sankey diagram illustrates the distribution of the power consumed into losses and effective power for a machine tool (Dietmair and Verl 2008)

In spite of difference in numbers, it is clearly revealed that energy-saving activities can be directed towards the machine tool to minimize idle energy consumption and to introduce more energy efficient systems (Anderberg et al. 2010). Energy information in machining processes requires being thoroughly monitored and analyzed. In this endeavor, it is important to first do a comprehensive research of energy consumption in machining (Vijayaraghavan and Dornfeld 2010).

2.2. ENERGY CONSUMPTION MODEL

To understand the energy usage in the machining system, an energy consumption model of the machining processes is indispensable. One study conducted by Munoz and Sheng (1995) examined operating parameters, such as depth of cut, speed, feed-rate, tool rake angle, in relation with environmental factors. It is regarded as the fundamental work for environmental-conscious manufacturing. Another study by Draganescu et al. (2003) presented the relationship between parameters, such as cutting force, torque, spindle speed, feed-rate depth of cut, and specific consumed energy using Response Surface Methodology based on experimental data.

A generic model is proposed by Dietmair and Verl to model energy consumption behaviour of machines and components based on a statistical discrete event formulation. Using the modelling framework, decisions can be made by prediction of the energy consumption of different configurations (Dietmair and Verl 2008; 2009). By energy analysis of four milling machines, a system-level environmental analysis is presented by Dahmus and Gutowski (2004). Cutting fluid preparation, machine tool construction, tool preparation, and cleaning are included in the analysis. Gutowski et al. proposed a thermodynamic framework to characterize the material and energy resources used in manufacturing processes which is the first step in proposing and/or redesigning more efficient processes (Gutowski et al. 2007; 2009).

Nevertheless, limited research in this area can be found. An accurate and complete energy model which solves the problem is still lacking. A mathematical model, independent on specific machine tool or settings rather based on the physical or theoretical energy model of the machine tool, will provide a powerful tool for reducing the energy consumption (Newman et al. 2010).

2.3. ENVIRONMENTALLY CONSCIOUS MACHINING

Environmentally conscious machining is another area that attract research efforts world widely. Studies of environmental impact of different manufacturing processes, e.g. grind-hardening process (Salonitis et al. 2006), joining process (Pandremenos et al. 2010), have been reported, which provide results of reducing environmental impact in production cases. In this paper, minimizing energy consumption is the main concern. Although it should be integrated in the system, currently energy data is not regarded as an integral part of the processes, such as parameters optimization process (Gupta 2005).

Sheng et al. (1995) stated that “In order to fully evaluate the trade-offs in these different alternatives, a set of quantifiable dimensions such as energy consumption, production rate, mass flow of waste streams and quality parameters need to be analyzed at the planning state”. A model-based approach to process planning is proposed for a rapid, robust estimation of energy and mass flows. Then, they presented the feature-based two-phase planning scheme, micro and macro-planning in detail. In a micro-planning process, predictive models are used to obtain process energy, machining time, mass of waste streams and quality parameters (Srinivasan and Sheng 1999). In macro-planning, the interrelationship between features is examined to generate overall sequence. Also micro and macro-planning schemes are integrated as an analytical platform (Srinivasan and Sheng 1999). A prototype process planner is designed based on the above scheme to interact with a conventional planner as an advisory environmental agent (Krishnan and Sheng 2000).

A multi-objective nonlinear programming model for environmentally conscious process planning is proposed by Jin et al. aiming at minimizing machining cost, time and environmental impact (Jin et al. 2009). Another model and methodology is developed by Rajemi et al. for optimizing tool-life and energy of a turning process, while considering the energy budget (Rajemi et al. 2010).

Mouzon et al. (2007) proposed operational methods for minimizing energy consumption and total completion time by multi-objective programming model. Through experiments, the dispatching rules provided an effective means to accomplish the optimization task.

Cannata et al. (2009) presented a procedure which effectively supports energy efficiency and/or environmental impact analysis, management, and control. An example application of the procedure, three scenarios of scheduling case study, served as an initial proof of concept.

Mani et al. (2009) re-emphasized on the importance of energy monitoring and discussed the potential use of energy information, and recommended research on energy efficient process planning.

Avram et al. (2010) developed a unified methodology of multi-criteria decision for sustainability assessment of use phase of machine tool systems. Economical, technical and environmental criteria are considered together, and a two-level analytic process is presented. Following that, they proposed a methodology to estimate the total mechanical energy requirements of the spindle and feed axes by taking into account transient and steady-state phases. Energy profile is obtained by careful monitoring of the machine tool and auxiliary equipments (Avram and Xirouchakis 2011).

Regarding online monitoring, current research applies part of energy-related signals for various monitoring purposes. Spindle motor current (Lee and Tarng 1999), cutting force (Huang and Chen 2000), energy per tooth analysis (Amer et al. 2005), electrical power (Al-Sulaiman et al. 2005), and audible energy sound (Rubio and Teti 2009) are used for tool condition monitoring, including tool breakage, tool wear and cutting parameters.

On the whole, it is evident that on the way towards sustainable machining, energy consumption should be considered systematically and concretely. The current literatures clearly suggest that improvement in one aspect of the machining process is not enough to achieve overall sustainability. In this paper, a framework of an energy-informed machining system is proposed to bridge the gaps.

3. FRAMEWORK OF ENERGY-INFORMED MACHINING SYSTEM (EIMS)

3.1. OVERVIEW OF THE ENERGY FLOW

To develop an energy-informed machining system, it is important to have a clear picture of the energy flow within the entire system. The energy flow is firstly studied in detail and critical energy components of the machining are structured in three levels. This energy flow analysis provides an insight of machining process, and knowledge on how energy is consumed in each part of different levels. The energy input to the system is composed mainly by electricity. Then, it is utilized by machine tools, auxiliary devices and infrastructures to fabricate the final products.

Figure-3 depicts an overview of the energy flow. The top-to-bottom arrows represent the actual energy flow in the system which is not visible directly. The bottom-up arrows describe the energy data that collected in each part.

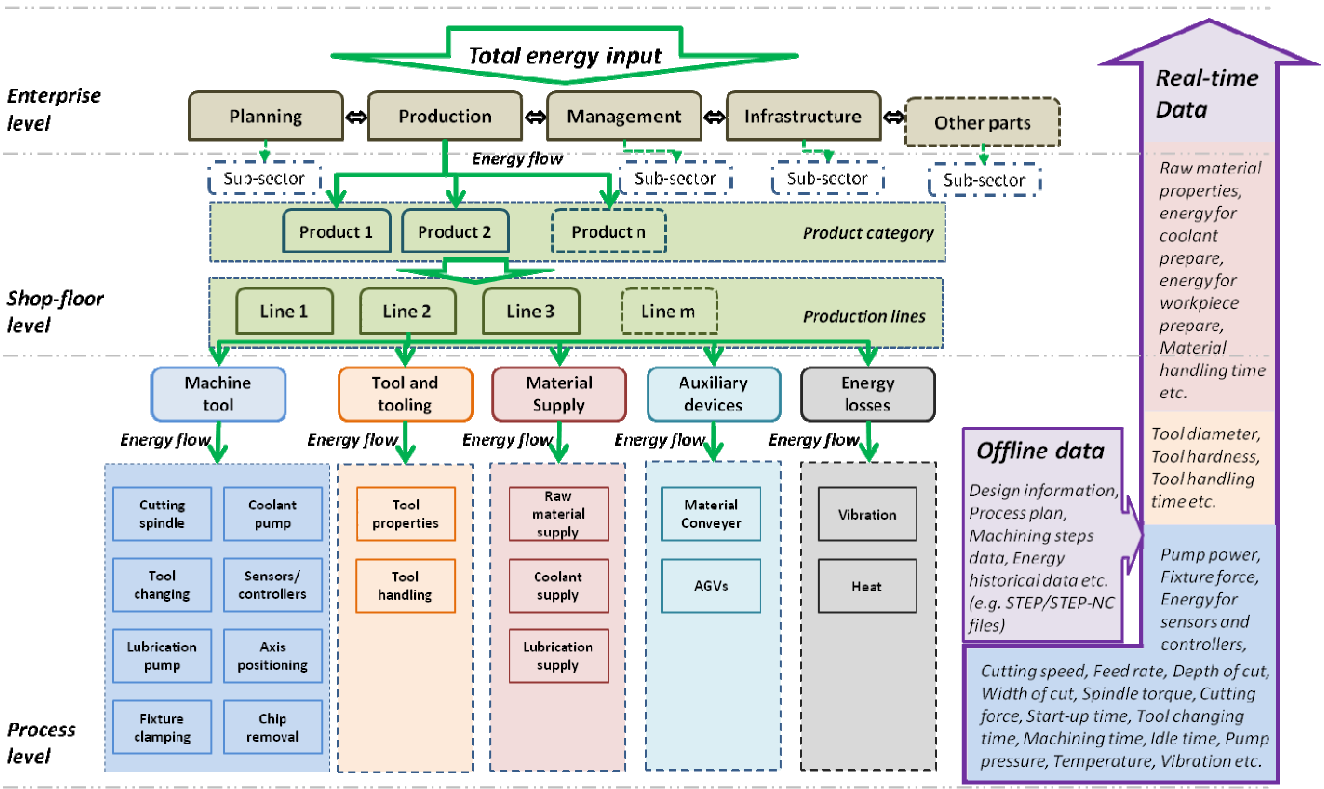

Figure 3 – Overview of the energy flow in a three-level structure

The bottom level is named as process level, where data are obtained in five basic parts, i.e. machine tool, tooling, material supply, auxiliary devices, and energy losses. During machining, on one hand, various sensors extract online data from both machine tool and auxiliary devices e.g. cutting force, vibration, while on the other hand, programmed machining parameters are imported as offline data, such as cutting speed, feed-rate, depth of cut and tool properties. Energy consumption for raw material, coolant, and lubrication supply is obtained as well for overall analysis.

At the shop floor level, the problems lie in task scheduling. Three primary states of equipment are identified namely machining, start/stop, and idle, which correspondingly, represent direct, indirect, and non-related energy usage. Moreover, energy consumption of a machine tool is considered with inclusion of machining time, start-up time, and idle time. At this level, systematic energy consumption optimization is looked into and intelligent scheduling algorithm is adopted to minimize indirect energy consumption.

In order to provide a comprehensive view of the energy consumption in an organization, enterprise level will cover all the departments, and infrastructure such as lighting, air-conditioning. But detailed discussion at enterprise level is beyond the scope of this paper.

3.2. FRAMEWORK OF EIMS

In a machining process, energy consumption can be expressed as,

$$E_{total} = E_{mc} + E_{idle} + E_{loss} \tag{1}$$

where E_{total} – total energy input to the system

E_{mc} – energy consumed in machining

E_{idle} – energy consumed in idling or waiting state

E_{loss} – energy losses in the system

During machining, energy usage is expressed as,

$$E_{mc} = E_{ac} + E_{other} \tag{2}$$

where E_{ac} – energy consumption of actual cutting

E_{other} – energy consumed in other component to support cutting, e.g. coolant pump

Based on energy model of specific energy consumption presented by Draganescu et al. (2003), the extension of the equation-2 is given as,

$$E_{ac} = V * \frac{\pi * D * F_{ct}}{C_{coef2} * v_f * a_p * Z * \eta} \tag{3}$$

where F_{ct} – cutting force

v_f – feed-rate

a_p – depth of cut

v_c – cutting speed

a_e – width of cut

Z – number of teeth

D – cutter diameter

η – machine efficiency

V – material removed volume

Energy consumption in idle state and different wastes is represented as,

$$E_{idle} = (t_{tc} + t_w) * E_{ip} \tag{4}$$

$$E_{loss} = E_{heat} + E_{vib} \tag{5}$$

where t_{tc} – tool change time

t_w – time to wait for next operation

E_{ip} – specific idle energy consumption per unit time

E_{heat} – energy transmitted into heat

E_{vib} – energy transmitted into vibration

In practice, signals such as cutting force, pump power, can be selected as indicators for E_{mc}. Information such as specific idle energy, start/stop energy, idle time should be used to calculate E_{idle} energy usage. Lastly, vibration signal or work-piece temperature can be used to ensure proper control of E_{loss}.

A framework of an Energy-informed Machining System (EiMS) is developed for conventional material removal machining processes, e.g. milling, turning, drilling etc. (Figure-4). The energy listed in equation-1 is covered in the EiMS. Basically, there are four modules in the framework, e.g. data collection, monitoring, analysis, and database, which are explained in following sections.

3.2.1. Energy data during machining

Integration of different sensors for monitoring has become a technology that has a major impact on machining (Zhou et al. 1995). In this data collection module, energy-related data is obtained by various machine tool sensors, e.g. cutting force sensor, vibration sensor etc., and the duration of each machining state is measured by controllers. These data are appropriately pre-conditioned and formatted, then sent to monitoring module locally, or remotely while web-based exchange standards, e.g. MTConnect (2008). MTConnect is an open light-weighted royalty-free standard to facilitate the organized retrieval of process information from CNC machines. It is designed to foster greater interoperability between shop floor equipments and software applications used for monitoring and data analysis (MTConnect 2008). As a matter of fact, intensive research activities imply the vast potential of adopting standards to support sustainable machining (Lee et al. 2010; Mani et al. 2010), and the efficient and effective means to adopt standards as enabler is demanded continuously.

3.2.2. Data monitoring

In the monitoring module, after rich data is obtained from machining processes, they are organized and managed in a hierarchical structure (Figure-3). Three different groups, namely direct, indirect, and waste machining consumption are formed to organize the data. The data obtained from machine tool part, e.g. cutting force, pump power, are organized in direct machining consumption. The data collected from tooling, materials supply, and auxiliary devices are regarded as indirect machining consumption. Heat and chatter emission is monitored in waste consumption. Hence, data can be easily accessed and manipulated for different purposes. Time measurements are recorded to give time duration, e.g. machining time, idle time, tool change time, tool usage time etc. Together with tool life estimation, these data will be used in the optimization process to minimize non-value adding energy consumption, e.g. idle.

3.2.3. Data analysis

Up to now, shop floor data have been successfully applied to tool condition monitoring (Byrne et al. 1995; Rehorn et al. 2005), and quality control (Ramesh et al. 2000; 2000). In sustainable machining, how to effectively use these energy-related signals is the main job of this module.

In this module, both real-time analysis and statistical analysis can be carried out. Real-time analysis focuses on online data processing during machining and supports real-time control, such as machining parameters optimization, quality control. Statistical analysis concentrates on comprehensive processing and historical data analyzing. Statistical results can also provide valuable information to other application e.g. CAD, CAPP, and ERP. In addition, machining parameters setting, energy usage prediction, and energy constraints are taken into account.

To ensure complete data representation and transfer from analysis module to other applications, standardized neutral format is an ideal means. STEP/STEP-NC standards, also known as ISO 10303 (ISO 1994; ISO 1994; ISO 1994) and ISO 14969 (ISO 2003; ISO 2003; ISO 2003), are adopted which provide a common basis upon which EiMS can be built. STEP-NC, designed especially for machining process, can carry complete information about design, planning, and production. Newly developed ISO 14649-201 machine tool data model (ISO 2011) starts to support environmental evaluation. This serves as a good start to further develop energy-informed machining data model.

3.2.4. Database

As there is rich data related to machining process, database needs to be constructed to manage different data in a trouble-free manner, and provide the machining configuration data to energy-informed analysis module. It is known that the energy consumption of an operation depends on not only machine tool, but also cutting tool, and material properties. Hence, machine tools database, cutting tools database, materials database, and energy ratings database will be constructed. Energy ratings database is a proposed base in this framework. It is mainly used to embed expertise knowledge in the EiMS to evaluate the energy consumption performance. With this ratings database, the energy consumption of a machining process can be assessed by the level of efficiency. If the energy usage of a machining setting is dropped into low level zone, the knowledge-based suggestions will be given to adjust one or more parameters.

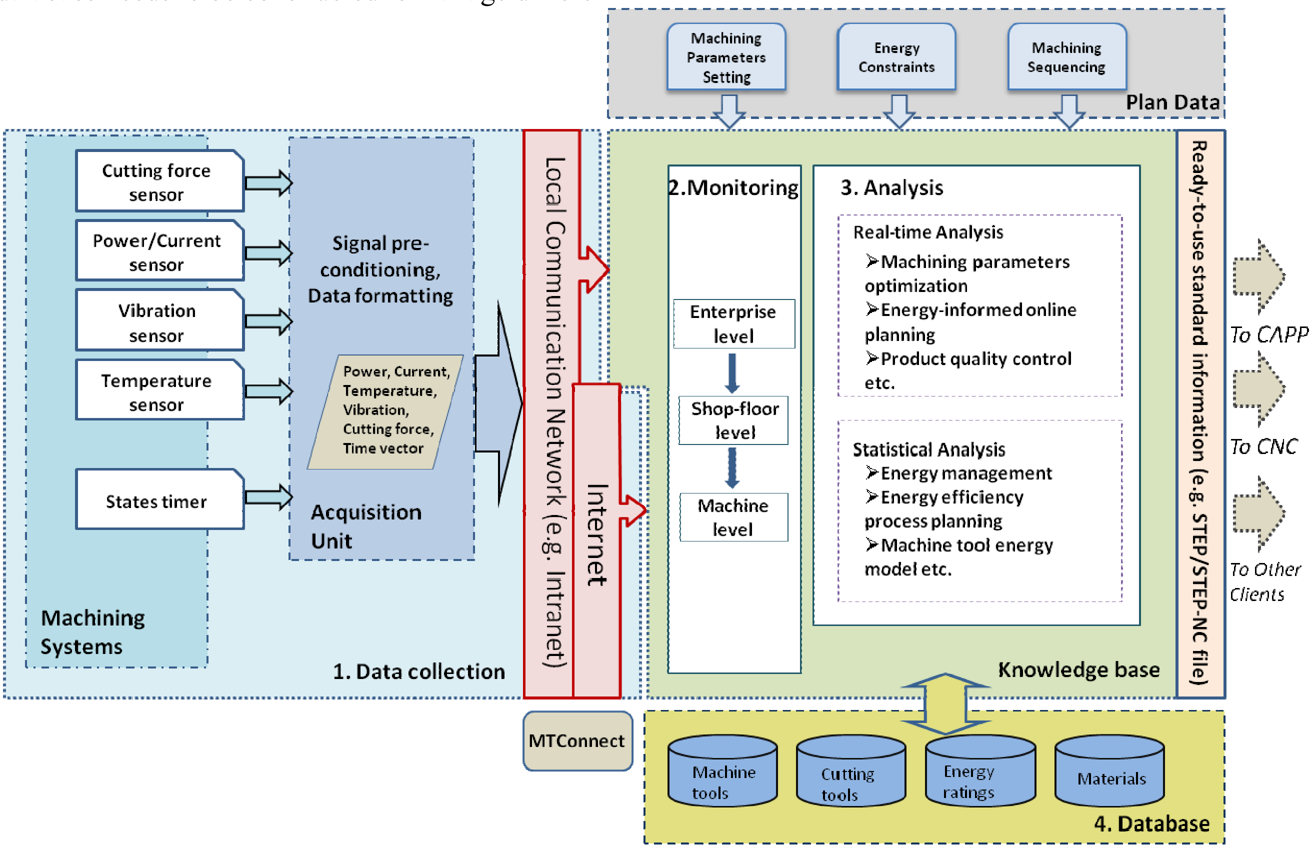

Figure 4 – Energy-informed Machining System (EiMS)

4. MACHINING PARAMETERS OPTIMIZATION

Attainment of energy information from machining process alone is not sufficient to improve systematic sustainable performance. Finding approaches to effectively and efficiently use these data is the key to upgrade performance. Machining parameters optimization, one of the key problems in machining research, is primitively exploited as means to utilize energy information in this paper. Even small improvement in energy cost can help the enterprise fight the competition in the global market (Gupta 2005). Those enterprises, involving intensive machining operations, can take larger benefits from the energy-informed parameters optimization in building up the digital factory.

An activity model of the machining parameters optimization is shown in Figure-5. This task is being undertaken in real-time analysis module. We take one of the energy-sensitive signals – feed-rate – as an example. The planned feed-rate is sent to the machine tool in STEP-NC file or machine tool codes. During the machining process, signals from sensors and events from CNC controllers are collected and transferred to energy monitoring module. After an increase of the energy consumption is detected, each energy components in equation-1 is analyzed, and it indicates that more energy is waste in vibration due to the aggressive feed-rate. Then multi-criteria energy optimization will be performed without sacrifice of productivity or quality. Finally, optimized feed-rate is fed back to update the actual machining. In this way, the goal of sustainable machining could be reached.

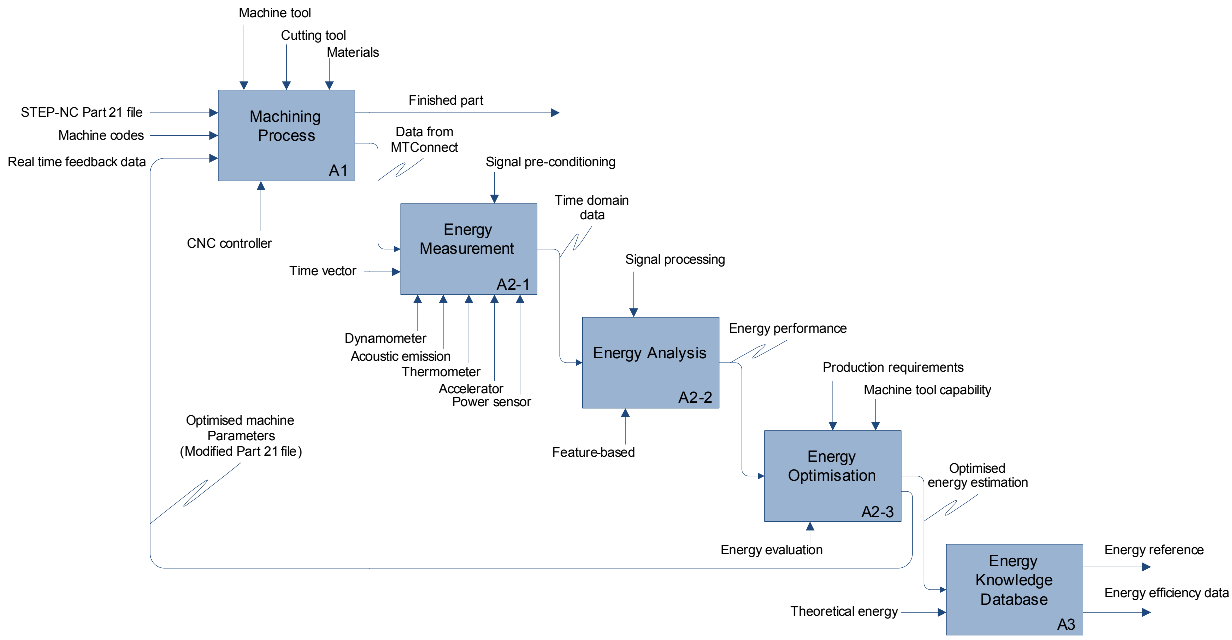

Figure 5 – IDEF0 of energy-informed machining parameters optimization

5. DATA MODEL FOR OPTIMIZATION

To integrate the energy-informed monitoring and analysis information into the CAx chain, a standardized neutral format that can represent and exchange data clearly is required.

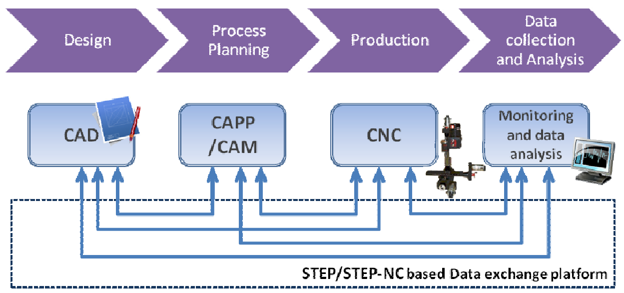

Figure 6 – Integrate energy information into CAx chains

For this purpose, STEP/STEP-NC is adopted. Literatures in this field indicate that although the bi-directional data flow enabled by STEP/STEP-NC standards improves the intelligence and interoperability of CAx chain, studies are leaning on the CAD to CNC direction. However, taking the benefits of the energy monitoring and analysis system proposed in this paper, the CNC to CAD direction is enhanced (Figure-6). To the authors' knowledge, energy information of machining is not included in STEP-NC standards.

ISO 14649-201 is a newly finalized part of machine tool data for cutting process (ISO 2011), in which environmental evaluation is firstly introduced. It is regarded as a good start to develop energy data model. Figure-7, the EXPRESS-G diagram illustrates the proposed data model for energy usage optimization.

ENTITY energy_usage_optimization is added as one of the attributes of machining_operation that is defined in ISO 14649-10. It has one subtype ENTITY machining_operation_scheduling. Two subtypes under machining_operation_scheduling i.e. ENTITY machining_parameter_optimization, and element_working_state. There are three attributes cutting_force, vibration, thermal_energy under entity machining_parameter_optimization, and feed_per_tooth, depth_of_cut, cutting_speed, specific_cutting_resistance are attributes of cutting_force. ENTITY element_working_state connect to attributes of entity maching_tool_element in ISO 14649-201, which model the energy data in each element.

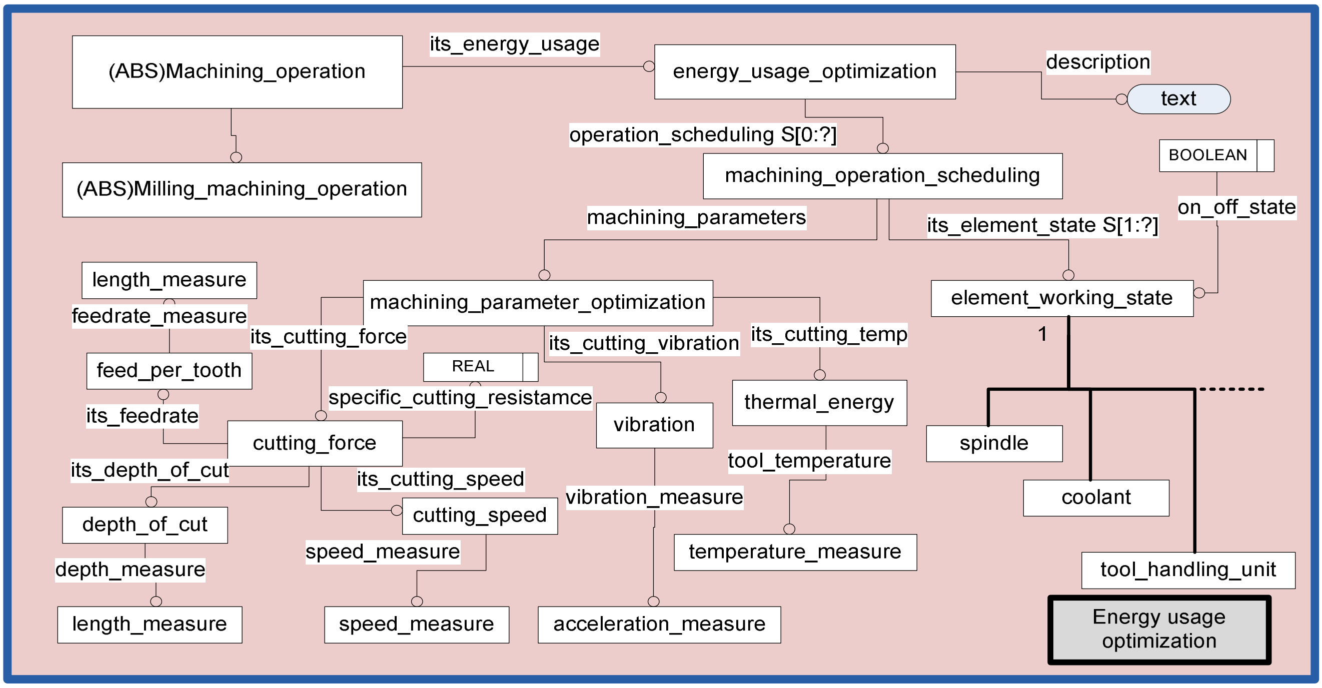

Figure 7 – Proposed STEP-NC data model for energy usage optimization

6. CONCLUSION AND FUTURE WORK

Despite the fact that the focus in machining has long been on productivity and product quality, it is important to re-evaluate the process within the context of sustainability. In short, due to the fact that machining systems are complex and dynamic, current energy efficiency research is not mature enough to improve the performance of industrial day-to-day practices, especially on shop floor activities. Through the study, two major observations are given.

Firstly, sustainability issues in machining processes are relatively new concerns, and up to now, studies are still at the early stage. Limited practical model and absence of theoretical mathematical model for energy consumption in machine tool systems are found from the literature survey. Therefore, better knowledge regarding the relationship between important components or parameters and energy consumption will offer great opportunities to improve the energy reduction in the CNC machining industry.

Secondly, the goal of improving sustainability requires proper utilization of the energy information to upgrade the system performance in all aspects. Current machining processes focus on achieving time or quality objective, so that it can bring the largest profit to the manufactures. Energy consumption is not considered as the main objective in the processes. Employment of energy information in machining processes is ineffective and integration of energy data is lacking. Thus, continuous research is required in the processes such as process planning, task scheduling, and environmental impact analyzing.

In this paper, the framework of an Energy-informed Machining System (EiMS) is proposed and explained to face the advances of sustainability requirements. The paper gives an overview of the energy flow in the machining system, which categorizes the energy data into logical groups to assist information management. Then, the authors outline functionality of each module in the proposed EiMS. Machining parameters optimization is chosen to demonstrate the mechanism of the EiMS, and the system can also be extended to processes e.g. energy-informed process planning.

Future work will be concentrated on developing energy consumption model of a machine tool system, and extending and modifying the STEP-NC based data model for energy-informed machining. A pilot case study to assess the performance of the proposed system is being considered. On the whole, the EiMS introduced in this paper actively supports sustainable machining in inclusive adoption among the digital enterprises.

7. ACKNOWLEDGMENTS

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