Energy-Efficient Machining via Energy Data Integration

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Abstract. Energy-efficient machining strategies are required to be implemented in daily practice to advance the competitiveness of the enterprises on global scale. Energy information, which currently not considered as an integral part of production data, is studied. A need is identified to integrate energy information into production program and solidify the knowledge for extensive reference. To effectively represent and share the data, standardized format is regarded as one promising approach, thus STEP-NC is adopted. The proposed data models are grouped into four, i.e. automated energy monitoring and recording, energy estimation and labeling, energy optimization, and machine tool energy performance. The developed schema is compliant and harmonized with other parts in STEP-NC standards. A case study is presented to add energy information to STEP-NC file. It can be concluded that standardized data format enables the integration of energy information into the production process and enhances its sustainable performance.

Keywords. Energy efficiency, STEP-NC, Data integration, CNC Machining.

1   Introduction

The world is well-connected and better-informed nowadays than ever before. It is also true to manufacturing domain. New requirements of modern manufacturing industry are placed, such as sustainable performance, minimum supply chain management cost, and optimal product lifecycle performance. Energy-efficient machining system is focused in this study, as it is the key area in metalworking industry for the future. To keep energy efficiently used, energy information from machining process shall be available to assist process planning or lifecycle analysis [1]. A series of simulation-based analysis and decision making systems are developed, focusing on energy usage and performance on product lifecycle level [2]. However, the ways to actually improve the daily practice in factories is still lacking.

The separated parties along the production chain desire to seamlessly share energy knowledge and data in a systematic manner. Data representation and exchange activities demand to be universal and consistent. This also contributes to significant savings on supply chain management cost, which is considered as the top priority of the enterprises for the next decade. With the rapid development in CAx, data communica-

tion problem exists between different activities, known as "Island of Automation". Even within each activity, the data exchange between different applications cannot be done without sacrificing accuracy or completeness. Energy-efficient machining system inherits the same problem. Therefore, how to standardize the energy consumption data and make it accessible and interoperable to different parties is focused in this research. ISO 14955 envisions establishing a method to evaluate environmental impact of machine tools, including eco-design and testing on metal cutting machines [3]. ISO 20140 aims to standardize evaluation procedure and data model for environmental performance of manufacturing systems [4]. Though both standards are still at the draft stage, it can be seen that standards are regarded as a good solution to remedy this problem. In this paper, existing STandard for Exchange of Produce model data (STEP [5]) is adopted to connect energy data model developed. The proposed data models are likewise open to be integrated with ISO 14955/20140 if it fits better.

2   Literature review

Energy-efficient machining covers the principle metalworking operations, e.g. milling, turning, and drilling. Computerized numerical control (CNC) machines, as the key players, are designed and widely adopted to perform these types of operation. Up till now, more than 70% of the jobs are done using CNC machines world-wide. Over the years, researchers in this area endeavor to figure out how energy consumption behaves in machining, and what are the influential factors. Energy modeling research started with examining cutter-workpiece interaction [6]. The theoretical analysis discovered some critical factors that affect the energy consumption, such as tool properties, materials [7]. Later, with the development of computing technology, statistic modeling based on rich data became popular [8]. These so-called empirical models use the production data to establish the relationship between the main variables and the energy usage. It allows the analysts to select only the interested/controllable factors. More factors yield to have impact on energy consumption, e.g. machining environment [9]. The factors that influence energy consumption are summarized in [10].
However, the studies are focused on one part of energy usage, i.e. cutting energy. Researchers dealing with sophisticated CNC machine tools nowadays realize the actual cutting energy is only account for 15%-25% of the total energy consumed [11]. Thus, discrete event modeling is introduced to model energy usage [12]. More components are being considered in this new approach, so a more complete energy profile can be obtained.

Moreover, advanced energy signal monitoring system is requested to collect and record data of influential factors. It is crucial to create adequate awareness of the energy efficiency information, but available system is still lacking. One application of energy efficiency monitoring and optimization system was reported in [13]. Automated monitoring process enables online energy optimization for a process. To apply the energy information collected during machining to other applications, data model should be able to hold the basic energy information and detailed energy report for reference. Databases are essential to sustain the analysis, as energy is related to di-

verse factors. A well-organized database should contain energy reference. Even the representative data from previous operations can help. All these aspects mentioned should be well considered to make the energy data integration successful. Figure 1 shows the IDEF0 diagram on how energy information acts to enhance energy-efficient machining processes.
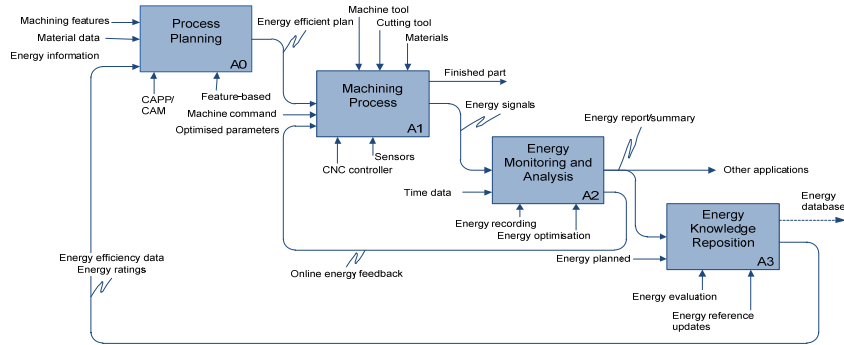

Fig. 1. IDEF0 diagram of integrating energy information into machining processes

3 Energy data model development

STandard for Exchange of Produce model data (STEP) is standardized as ISO 10303 [5], which is a family of standards defining methodology for describing product data throughout the lifecycle of a product. STEP-compliant Numerical Control (STEP-NC) is designed for machining industry. It is task-oriented and enables bi-directional information flow. It is standardized in ISO 14649 [14] and ISO 10303-238 [15]. ISO 14649 is used in this research for data modeling purposes, considering its straightforward data structure and adequate manufacturing data. The proposed energy data models are developed using EXPRESS language (standardized in Part 11 of STEP standard [16]) and presented using EXPRESS-G (graphical representation of EXPRESS) in a more understandable manner.

Four groups of data models are proposed to hold energy information, i.e. data models for automated energy monitoring and recording, energy estimation and labeling, energy optimization, and machine tool energy performance. The suggested data model is connected to and harmonized with other parts in ISO 14649. Detailed diagrams are omitted due to page limits.

3.1 Automated energy monitoring and recording

Before the actual machining happens, energy data collection can be planned. Inspired by the traceability data model developed by Campos et al. [17], new functions are modeled and connected to nc_function in Part 10 to automate the monitoring process. A holistic view of this group is illustrated in Figure 2, with proposed nc_functions. All the entities can be Sub-Grouped (SG) into three. SG I functions are designed to hold information of current system, including Obtain_time, obtain_sensor_data, and

obtain_machine_tool_data. SG II functions aim for holding energy monitoring data. They can be inserted in the NC program, and enables appropriate data acquisition automatically. Start_energy_monitoring_sensor_data, stop_energy_monitoring_sensor_data, and signal_source_identified belong to this group. SG III defines the data structure of energy report for reviewing or auditing. Enable_energy_report, energy_report_format, and data_for_generate_energy_report are core functions.
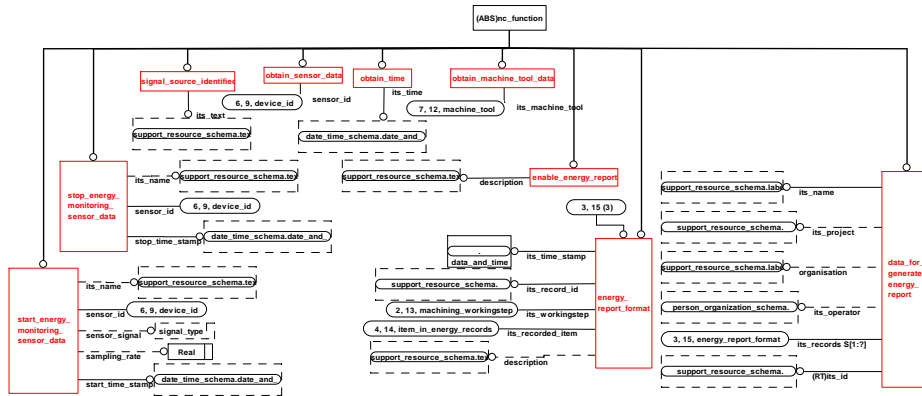

Fig. 2. Data models for automated energy monitoring and recording

3.2 Energy estimation and labeling

The influential factors are considered to develop this part of data model. Figure 3 illustrated the major entities proposed. As one attribute of ENTITY energy_usage_label, ENTITY machining_energy_model is abstract supertype of machine_tool_energy_model and main_cutting_energy_model. The former is used for systematic energy profile, while the latter is focused on actual cutting energy. Attach the estimated energy usage to NC program is called energy labeling. The main purpose is to indicate the energy used for the current project and its constituent elements, offering a brief view to the process reviewer or process planner.
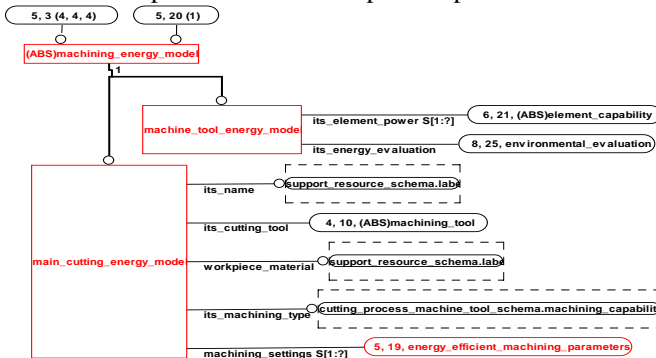

Fig. 3. Data models of machining_energy_model in EXPRESS-G

Utilizing the proposed data model, energy labeling can be done in two ways, i.e. energy estimation for selected workplan/workingstep and energy summary for the project.

3.3   Energy optimization

Currently, energy optimization is not regarded as major or even one concern of most machining. Online energy optimization is rarely supported. Realizing the need, energy_optimization_data is proposed to hold data for machining. It allows the controller to adapt the settings autonomously for following steps based on specified energy model within the max value permitted and other availability at the shop floor. It enhances the smart controller performance in an energy-efficient fashion.
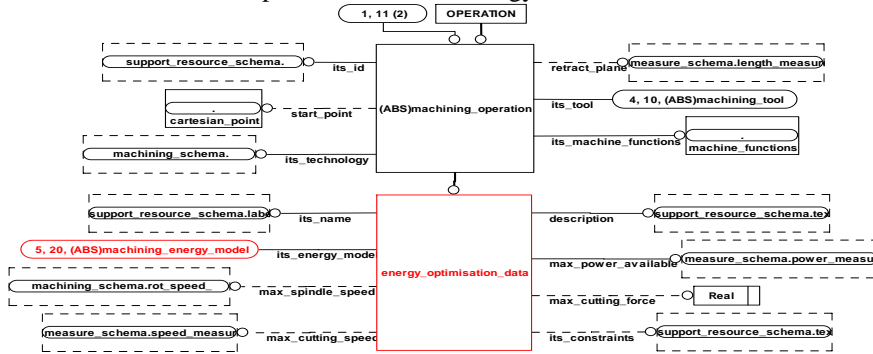

Fig. 4. Proposed energy_optimization_data and its relationship with machining_operation

3.4   Machine tool energy performance

A well-organized database is critical for a comprehensive energy analysis. It should contain energy reference as a part of machine tool performance. To include this piece of information, it is best to attach it to machine tool database. This is because generally energy performance of a machining process is related to the machine tool in use, its structure, capability and condition. Produce the same part on different machine tools often results in different energy usage pattern. Hence, we proposed ENTITY energy_performance_reference (Figure 5) to store the energy history of the machine tool, connected to standard_machining_process of machine tool data model.
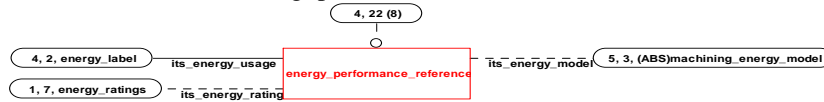

Fig. 5. ENTITY energy_performance_reference

A machining energy model will be specified for an energy performance record, as well as its ratings. How to quantify the energy efficiency index in a meaningful and standardized manner can be further explored incorporate with ISO 20140. This is included as future research work.

To sum up, tighter data flow and integration is highly required. The energy information data model proposed in this section enhances data integration for energy-efficient CNC machining processes, and fully harmonized with existing parts in STEP-NC standards. The EXPRESS-G diagrams are developed using ST-Developer version 14, STEP Tools. Inc., USA.

4   A case study

A case study is conducted to demonstrate the use of energy data model in Example 1 of ISO 14649-11 [18]. To produce this part, five workingsteps are required, i.e. planar face finishing, hole drilling, hole reaming, pocket roughing, and pocket finishing. Originally, there is no energy information in the sample NC program.

We implement the developed data models in section 3.2 to modify sample STEP-NC file. Energy information is added. The calculated energy summary of the production project is attached at the end of the file. It estimates how much energy is expected to be consumed before it happens. Segments of modified part 21 file are shown below. One can easily locate the basic energy consumption summary at line #200.

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION(('EXP1 WITH ENERGY INFORMATION'),'1');
FILE_NAME('EXP1_E.STP','25-06-2012',('TAO PENG'),('UoA'),'','','');
FILE_SCHEMA((('COMBINED_SCHEMA','ENERGY_INFO_FOR_MACHINING_SCHEMA'));
ENDSEC;
DATA;
...
#43=PLANAR_FACE('PLANAR FACE1',#18,(#27),#31,#36,#40,#42,$,());
#44=MACHINING_WORKINGSTEP('WS FINISH PLANAR FACE1',#5,#43,#27,$,#198);
...
#108=WORKPLAN('MAIN WORKPLAN',(#44,#64,#65,#93,#94),$,#107,$,#199);
#109=PROJECT('EXECUTE EXAMPLE1',#108,(#18),$,$,$,#200);
...
#194=CUTTING_FORCE(0.04000000, 12.00000000, 2.50000000, 20.00000000, $);
#195=MAIN_CUTTING_POWER(#194, $);
#196=ENERGY_EFFICIENT_MACHINING_PARAMETERS(#195,100.00000000,"DRY");
#197=MAIN_CUTTING_ENERGY_MODEL('ENERGY WS FINISH PLANAR
FACE1',#20,'STEEL',.MILLING_CAPABILITY.,#196);
#198=ENERGY_USAGE_LABEL(2789.500000000, #197);
#199=ENERGY_USAGE_LABEL(8425.00000000, $);
#200=BASIC_ENERGY_CONSUMPTION_DATA($,
8425.00000,(2789.500000,$,$,3975.500000,1660.00000),$,'REPORT EXP1',$);
ENDSEC;
END-ISO-10303-21;
```

5 Discussion and future work

The drive for increased competitiveness, reduced energy consumption and overall cost, pushes for energy-efficient machining operations. It has become evident that machine tool vendors and CNC users are making great efforts to improve the energy efficiency, both on machine tool itself and operation strategies. However, it is observed that insufficient energy data interoperability from CNC machining to other applications remains as one of the key issues in limiting energy-efficient machining processes. Thus it yields a necessary and crucial step to include energy information into the data sharing. The proposed data models for covering energy information purposes, augments the existing STEP-NC data model. It is important to collaborative machining environment in which energy monitoring, analysis and optimization can be exercised based on the developed data model.

For the next generation of intelligent CNC machines. The possible applications enabled by this data model are beyond the case study. For example, automated energy monitoring can be achieved by inserting standardized energy monitoring functions into the production file, and while executing the file, the STEP-compliant smart CNC controller can automatically activate requisite sensor to capture the data, and store the data in a consistent manner. The planning system can select the most satisfactory signal and effective sensor if there is more than one sensor on the CNC. The recorded energy profile can be recorded in a separate file, which is ready for post machining analysis. With the energy footprint, one can re-evaluate the energy consumption planned at the beginning, and update the energy pattern. Other areas that may benefit from the energy information data model includes but not limited to,

- Design for manufacturing
- Energy-efficient process and production planning
- Resource management
- Enterprise investment guidance

Though attentions are drawn in this field, research results are relatively preliminary. Future work will focus on optimizing energy consumption for machining practices, and explore the possible approach to control the CNC machines adaptively based on the data model. Development of software tools in assisting energy data monitoring, analysis and optimization is another useful work planned in the near future.

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