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Developing energy estimation model based on Sustainability KPI of machine tools

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Abstract

Since eco-efficiency of manufacturing resource has been emphasized, various sensors to measure energy consumption have been developed and machine tool builders also provide data of energy consumption of their own products. Due to the variety and complexity of machine tools, however, an enormous amount of data is generated and can lead to uncertainties in further interpretation. The data relating to energy consumption can be classified into process parameters and machine specifications. In order to estimate the energy use that a new machine tool utilizes, the relationship with various performance indicators of the machine tool and a process plan should be examined. The challenge is how to link the machine specifications and process plan in order to obtain actual energy consumption. This paper proposes an approach for deriving an energy estimation model from general key performance indicators of the sustainability of machine tools. For the detailed application, the proposed methodology is applied to the laser welding process of an automotive assembly line and the milling process of an aircraft part manufacturer. The paper describes the methodology for finding the parameters necessary for calculating energy use and to develop the energy estimation model by utilizing experimental data.

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Keywords: Sustainability; Key performance indicator; LCA; Energy-efficiency; Milling machine; Laser welding; Sustainability; Machine tool

1. Introduction

A tremendous amount of data has been collected from the manufacturing resources on the shop floor of modern factories. However, in many cases it is difficult to say which machine tool is the low-efficient resource because there are various perspectives of evaluation energy efficiency and methods to reduce the energy use of each machine tool. To solve this limitation, many frameworks to evaluate energy efficiency of manufacturing resource have been developed. Herrmann proposed the approach of two lifecycles about product and machine tools and stated sustainability of manufacturing should be evaluated with these approaches (Herrmann et al. 2007). He also showed the general model about various machining processes such as milling, turning, grinding, and laser (Duflou et al. 2012). Avram developed an energy calculation model based on unit processes and pre-measured energy data from an experimental database (Avram and Xirouchakis 2011). An evaluation framework based on accurate information from the machine process unit is shown by Karnouskos et al (Karnouskos et al. 2009) but this method was an overall performance or generalized model. For this reason it is not suitable for predicting the actual energy of a specific machine tool. Thus, the appropriate framework for calculating actual energy for industry with respect to their own products is required. This research proposes a framework with consideration of the electrical characteristics of machine tool components and the process producing target product. The approach required for calculating actual energy evaluation is discussed in section 2 from the perspective of the structure of KPIs. Section 3 describes the integrated approach with function analysis and process analysis to consider the factors influencing the energy consumption. A case study is provided in section 4 to show the examples of the analysis results about milling machine and laser welding. The contribution shown in the case study and future work on the proposed approach are discussed in section 5.

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2. Structure of KPIs in different field, LCA, Sustainability, Application level

The requirements for developing the framework for actual energy evaluation are an upscaled approach and decomposition of the analysis target. Since the assessment of sustainable performance in manufacturing has become an important issue, performance evaluations are done by individual and customized key performance indicators (KPI) as introduced in (Thoresen 1999). As these performance indicators address the production line, plan or enterprise, a multi-level approach for energy efficiency performance has been considered. However, the indicator is not suitable for assessing process units or machine tools as concluded by (Bunse et al. 2011). A gap between strategic and operational performance evaluation is seen and evaluation approaches on the process unit and machine tool have to be considered. The absence of a clear picture of energy and resource consumption of machines and production lines is today one of the main barriers to the evaluation approach of product units and machine tools, as stated by (Diemair and Verl 2009). Moreover, comprehensive information of actual energy demand is required for the evaluation of the energy consumption and the environmental performance of machine tools as indicated by (Lareck et al. 2011). On the process level, Schleicher confirm the lack of data and imperfect information (Schleich 2009). The lack of information for the operating performance and the machine tool usage is stated by (Zeain 2012). An evaluation framework based on accurate information from the machine process unit is shown in (Karnouskos et al. 2009).

As figure 1 shows, the ongoing FP7 project FoFdation revealed a cross-level framework that is able to integrate energy efficiency measures in an adequate performance assessment system for manufacturing companies on the shop-floor and machine tool level. This approach links the available performance indications and can support decision makers in assessing the impact and effects of energy efficiency measures on the process unit level and also evaluate the overall business performance. An assessment of the process unit level must be based on adequate measurement equipment in combination with an adequate evaluation framework. This is needed as highly variable products have to be assessed with as much detail and accuracy as possible. This is challenging as detailed information, e.g. measurements and measurement values (MV) can be upscaled for higher application levels, e.g. line, factory or used for KPI calculation, whereas already aggregated information cannot be downscaled, e.g. to a machine tool or subcomponent level from MVs to KPIs. For this reason, an upscaled approach and decomposition of product unit and machine tool are considered as the requirements of the framework integrated with function analysis and process analysis.

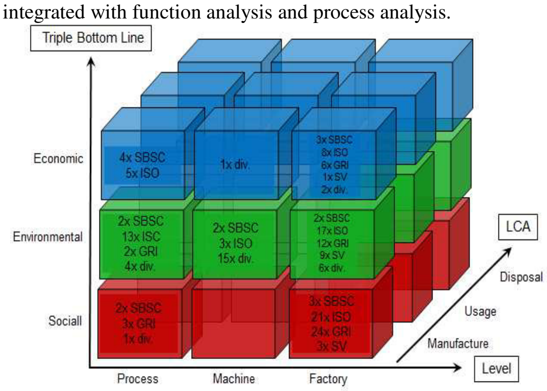

Figure 1. Clustering of metrics and indicators within FoFdation

3. Integrated approach

3.1. Integrated approach

In this section we gather two approaches about the function and process of machine tools to estimate actual eco-efficiency. These two aspects were emphasised by Herrmann because they are the intersection of the lifecycles of product and machine (Herrmann et al. 2007). With regard to the machine side, the eco-efficiency of the factory is the main factor but on the product design side the process is the more important factor. For this reason, this paper presents a holistic method developed to resolve the following questions.

- How can be the performance of each component be estimated?
- How can be the eco-efficiency of various product cases be adjusted?

3.2. Functional approach

Function orientation is primarily represented in the development of complex technical systems such as in the automotive sector. It is considered a review tool to meet consumer requirements. The development and testing of the functionalities defined can be challenging since complex mechatronic or hybrid systems such as vehicles, buildings, and machine tools fulfill their defined functionality by employing various consumers. Regarding technical specification, the evaluation of the functionality and its attributes, i.e., energy consumption, must be done on the component level.

A function is defined as the outcome, task, action, or attribute of an object or component (Schleich 2009). The functional description is general and independent of the system design. Corresponding components can be mapped to one of five main machine functions, as illustrated below for a generic sample machine tool.

The assignment or mapping of mechanical/electrical machine components to the functions is specific for each case. Figure 2 shows this transition from total energy consumption via functional level and functional mapping to mechanical/electrical component level with five main machine functions defined here.

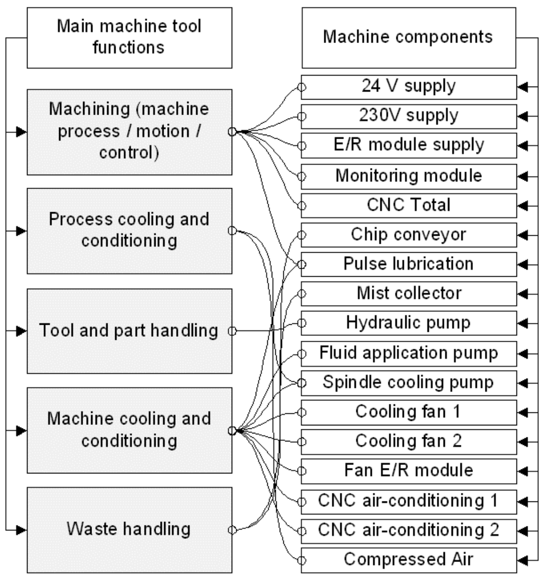

Figure 2 Main machine tool functions and its example components for a cylindrical turning machine

CD Laser C5G (COMAU)	Machine operation (machining process, motion and control)	Process conditioning and cooling	Workpiece handling	Tool handling, or die change	Recyclables and waste handling	Machine cooling/heating
24 V supply	100%					
CNC air-conditioning						100%
Drives supply	100%					
Cooling Fan 1					100%	
Cooling Fan 2					100%	
Generator	100%					100%
Cooling pump						100%

Figure 3. Cluster matrix for functional analysis according to ISO 14955 (ISO 2014)

As metalworking machine tools cover a wide range of different types, sub-types and sizes, a machine tool is described by its functions (see Figure 3), which might be realised by different machine components. This allows a generalised approach for a wide range of machine tools in order to evaluate environmental impacts of machine tools and the change of environmental impacts over time. A machine tool should be described by the following functions in relation to energy efficiency during the use stage (This functional description is a proposal to facilitate analysis and problem solving in relation to the energy efficiency of a machine tool during the use stage):

- Machine operation (machining process, motion and control);
- Process conditioning and cooling;
- Workpiece manipulation;
- Tool handling, or die change;
- Recyclables and waste handling;
- Machine cooling/heating.

NOTE: With these generalized functions any machine tool is seen in a generalized view, independent from the implemented machining process and/or design of the machine tool.

3.2.1. Machine operation (machining process, motion and control)

This function summarizes the target function of the machine tool, i.e. all energy supplied needed to realise the primary machining process.

- Machining process: 'Machining process' summarizes the realisation of the machining processes, e.g. cutting velocity, electro-discharge process, laser beam for a cutting machine, process force and working stroke of a press. Typical components for the function 'machining process' are the main spindle of a turning machine, the tool spindle of a machining centre, the generator of an electro-discharge machine, the slide of a press.
- Machining motion: 'Machining motion' includes motions needed during machining of a workpiece except machining process motions. Examples of 'machining motion' are feed motion of a turning machine, positioning motion of a rotary table, feed motions of a laser cutting machine, closing and opening of a press. Typical components for the function 'machining motion' are linear and rotary axes of a machining centre with their drives and power supply systems, rolling and sliding guidelines, ball screws, bearings, gears, belts and pulleys.
- Machine control: 'Machine control' summarises the control of the machine, generally the numerical control, for automatic sequence control, monitoring systems and measuring systems. 'Machine control' may also contribute to non-machining functions, e.g. tool handling. Typical components for the function 'machine control' are the numerical control systems, PLC, displays, sensors, decoders and encoders, lighting of the work space, frequency converters, voltage transformers, relays, and touch probes.

3.2.2. Process conditioning and cooling

This function combines all cooling, heating and conditioning that is process-related in order to keep the temperature and other relevant conditions of the working volume, the tools, the fixtures and/or the workpieces within limits. Process conditioning may be seen as a value adding function in order to achieve a constant machining process, e.g. lubrication for grinding, die lubrication for presses.

NOTE: Process conditioning and cooling is sometimes combined with machine cooling/heating. Typical machine components for the function 'process conditioning and cooling' are cooling pumps related to process coolant, cutting/forming fluid cooler, die lubrication fluid cooler.

3.2.3. Workpiece manipulation

'Workpiece manipulation' may consist of workpiece changing, workpiece grasping, workpiece clamping, workpiece manipulation, workpiece lifting, infeed of raw material, measuring of workpieces on the machine tool. Typical machine components for the function ' workpiece manipulation' are pallet changer, workpiece manipulation robot, hydraulic clamping devices, and pneumatic chucks. On forming machines 'workpiece manipulation' is mostly done by a destacker, centering stations, workpiece lifters in dies, workpiece ejectors, workpiece manipulation devices (e.g. robots, gripper bar transfer systems), stacker.

3.2.4. Tool handling

'Tool handling' may consist of tool changing, tool grasping, tool clamping, tool storage, measuring of tools on the machine. Typical machine components for the function 'tool handling' are the turret of a turning machine, hydraulic clamping devices, pneumatic chucks, tool changer, tool magazine, system with compressed air to clean tool holder.

3.2.5. Die change

'Die change' may consist of die and automation tooling transport to/from interconnection points into a machine tool, die clamping, die storage, preparation of tooling for automation systems, coupling/decoupling of energy needed for e.g. part forming in hydro-forming processes or auxiliary die functions like lifters, coupling/decoupling of die lubrication supply. Typical machine components for the function 'die change' are moving bolster or die cart, die pusher/puller, die clamps (hydraulic or electric or electro-hydraulic or hydro-pneumatic or magnetic), manually operated mono-couplings, automatically operated docking systems equipped with multi-couplings and/or electric plugs.

3.2.6. Recyclables and waste handling

This function summarizes handling of chips or scrap, handling of cutting fluids including separation and filtering, handling of dust and fumes, handling of dirt. Typical machine components for the function 'recyclables and waste handling' are a chip conveyor or scrap conveyor, filter systems, exhaust systems, systems with compressed air for chip transport.

3.2.7. Machine cooling/heating

This function summarizes all cooling and heating that is independent of the machining process. 'Machine cooling/heating' does not add value to the machining process itself. Machine cooling/heating is applied in order to keep temperature within limits, so that machine components are not damaged or distorted e.g. keep the temperature of the control cabinet within operational limits, keep the temperature of a high speed spindle within safety limits, keep the temperature of the machine tool within limits in order to prevent any thermal influences on the kinematic structure of the machine tool, keep oil temperature within operational limits. Typical machine components for the function 'machine cooling/heating' are fans, cooling systems for control cabinets, water coolers, cooling pumps, cooling/heating of guideways.

3.2.8. Sub functions

The generalized functions may be divided into sub functions in order to detect relevant energy flows. Figure 4 shows one possible division into sub functions.

3.3. Process approach

Research has been done on estimating the energy consumption for specific machines. Avram and Xirouchakis developed an estimation model evaluating the energy requirements for 2.5D machining with experimental data about specific unit features (Avram and Xirouchakis 2011). Gregory et al. introduced an energy estimation model for optimal trajectory planning for robot arms (Gregory et al. 2012). Process planning is another factor for influencing eco-efficiency because optimised planning reduces the environmental impact with the same machine tool. Furthermore, the effect on eco-efficiency performance of whether the machine tool is equipped with an efficient spindle motor and bar feeders lacks confirmation in the case of specific process plan. If a given process plan includes frequent usage of sub-efficient components, the machine tool consumes more energy than used by another machine tool.

The process approach is based on process considerations and is also represented in the ISO 14649-201 standard (ISO 2011b). The process plan consists of a part program and product data. The part program is the language of machine tool controller and expresses the motion of machine tool. The analysis steps are as follows. To calculate the environmental impact, the ISO standard about machine tool data model formalised as ISO 14649-201 describes the standard process and environmental impact data. The part program is represented in various languages such as G-code, APT, and STEP-NC. G-code is widely used in current commercial controllers. It contains only axis motions and some functions to manipulate spindles and tool changers. That is, it has a limitation in that it does not contain high-level information to calculate energy consumption. ISO 14649 gives all procedure and consideration of process planning and has an advantage that environmental impact can also be calculated (ISO 2003). Furthermore, a new part of ISO 14649, the machine tool data model, covers representation of the environmental impact. The environmental data model provides evaluation of a unit process

- This model is an analytical approach for the estimation of the variable mechanical energy requirements for a machine tool with experimental verification
- The model takes into account the machine tool layout, moving masses, spindle, and bar feeder.
- Process power (laser energy, motor energy), tool location

Another ongoing FP7 project, called RLW Navigator concerns a new laser welding process for car door assembly. As part of this, an EcoAdvisor using an energy estimation model has been developed which is able to calculate consumed energy for the process using experimental data. This model can show the actual energy use for a specific part and provides practical information for the machine tool user. One of the authors developed the holistic energy estimation model for a machine tool which covers making the scope of evaluation target and analysis of the function. The energy consumed by the robot is calculated by collecting the results of paths where laser welding is processed. A previous estimation model of milling machines focuses on the motion analysis of machine tool components. The proposed model for remote welding is based on motion analysis and includes consideration about laser power simultaneously.

- NC program of controller: The first step is to read an NC program from the controller. The NC program of milling and turning is written in G-code. The parameters of each path are collected from an NC program and are the basic input to analyse the energy of the machine tool.
- Kinematic analysis: The extracted path means the positions of a machine tool on the trajectory and can be represented by an end-effect of an open-loop manipulator. Inverse kinematics is used for finding the motion of joints in the machine tool.
- Kinetic analysis: Kinetic analysis derives the work to reach the end position of each joint. The joint motion is required to calculate the kinetic energy of the machine tool. The assumption is that the energy is directly proportional to the work occurring by joint motion. The kinetic energy of the milling processes is derived from moving masses and cutting forces. The moments of inertia and torques of joint axes are required additionally in the case of a robot arm.
- Energy consumption model of Auxiliary devices: In addition to physical motion of tools, auxiliary devices also consume an amount of energy and generate emissions. For a laser machine there is a chiller, and the laser source to be considered. In a milling machine a hydronic pump is an additional device consuming energy. Coolant use is also a factor affecting environmental impact of metal cutting.
- A simple linear value for time is used for the model derived from experimental data.
- The collection of experimental data: Acquiring all factors affecting eco-efficiency in the derived model is complex. Approximation to ignore minor factors is required to fill the gap between estimated data and actual phenomena. In the case of energy consumption of a robot arm, the work of joint motors differ from the actual energy use. A possible approximation method is the classification of the energy profile and the usage of the slope trend of energy profiles.
- Summation and display: The final step is to display the result of the energy estimation with relevant factors for overall decision making. The productivity factor is more important than the environmental factor. The feasibility, process optimization, lead time, and cost are high priority factors, too. Overall factors should be reported as well as the energy estimated.

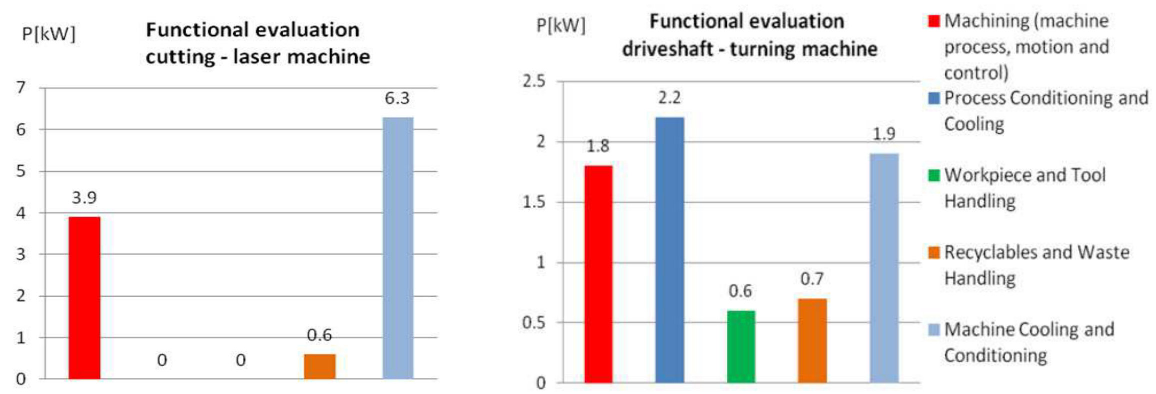

Figure 4. Functional analysis according to ISO14955 with laser welding robot on the left and milling machine on the right.

4. Case study of milling machine and laser welding robot

In this section, we now illustrate how the proposed approach can be used to estimate energy use which is a significant factor in environmental impacts for machine tools in functional analysis and process analysis for remote laser welding. COMAU has commercialized a remote laser welding robot called "Smart Laser" which is the target robot in this case study. In this case we limit the scope of the estimation to the machine tool itself and ignore the impact of water and hydronic suppliers provided by building.

4.1. Functional analysis

In the following the component classification and energy evaluation according to the ISO14955 (ISO 2014) was performed. For the case study the laser welding robot SmartLaser CSG was chosen. Based on the e-scheme of the machine system and the connected load of each system component, the following components were selected for further evaluation. According to the ISO14955 requirements and because of measurement uncertainties, the cumulated sum of all selected components has to cover at least 80% of the total power of the entire production system. Thereby at least all components are relevant for the evaluation that account for more than 20% of the entire energy supplied to the system. Based on these requirements the following system components were chosen and clustered into the six machine tool functions according to ISO14655

$$P_{sys} \le \frac{\sum_1^n P_n}{0.8} \qquad (1)$$

$$\{P_n | P_n \ge 0.2P_{sys}\} \qquad (2)$$

Psys= Average power consumption of entire machine tool during reference process. Pn = Average power consumption of each component n of the machine tool. The results of the calculation can be seen in figure 5.

4.2. Process analysis

Remote laser welding, which has benefits for productivity and for energy saving, has received attention for automotive assembly lines, but introducing this innovative equipment needs a significant decision. Major physical components of an RLW workstation are laser source, robot arm, and cooling of physical components. Process analysis is carried out along the sequence described in section 3.3.

- NC program from the controller: In the case of robot arms the code interpretation is required because commercial offline programming systems for welding robots do not use a standardized code but specialized ones. An NC program is a basic input to analyse the energy of the RLW process and contains laser power and path data including welding speed and path point.
- The target robot has four robot arm joints and three laser manipulators consisting of lens zoom and scanner rotating motor. The four robot arm joints are the factors considered because scanner manipulation consumes much less energy than the robot motion. To find the joint angles of individual robot arms inverse kinematics from welding points was carried out and follows the Denavit-Hartenberg parameter model, the data of four arm joints consisting of fixed angle of X axis and of variable angle of Z axis. Joint angles of robot arms to move to each welding point were derived by inverse kinematics from converted welding points.
- The assumption of the kinetic analysis is that the electric energy of the robot motion increases with change of work of the joint motor. The joint velocity and initial angle of the robot arm are derived from inverse kinematics. The torque and work consumed by robot motion are calculated.
- The cooling system is also equipment which should be measured because the cooling energy of the laser source is higher than other welding processes. In order to generate the laser, a large amount of heat occurs in the laser source which is cooled using a water cooling system. To collect compensation data, an energy measurement device is installed in the welding equipment. It consists of a power cell, data acquisition board, and data monitoring software. The cables of the power cell are clamped to the power supply lines of each device. The power cell measures electronic power and transmits it to the data acquisition board. The board converts analogue signals into digital signals with 5000 Hz sampling. The data monitoring software collects the signal and stores it in a text file. For process analysis welding robot and controller screen are captured by a video camera.
- EcoAdvisor shows the process parameter / design change to evaluate alternative shape related to eco-efficiency. The final step is to display the result of the energy estimation with relevant factors for overall decision making. The productivity factor of the assembly line is more important than the environmental factor. The feasibility, process optimization, lead time, and cost are high priority factors, too. Overall factors of the assembly line should be reported as well as the energy estimated.

5. Conclusion and Future works

In this paper a holistic approach to estimate actual eco-efficiency of machine tools has been proposed and shown to be useful in remote laser welding system for automotive welding line. The proposed approach is improved by validating with metal cutting machine tools and other robot systems as well.

Acknowledgement

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