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Standardizing environmental performance evaluation of manufacturing systems through ISO 20140

Hitoshi Komoto[a], William Z. Bernstein[b,*], Soonjo Kwon[c,d], Fumihiko Kimura[e]

[a] National Institute of Advanced Industrial Science and Technology, Namiki, 1-2-1, Tsukuba 305-8564, Japan
[b] Engineering Laboratory, National Institute of Standards and Technology, 100 Bureau Dr, Gaithersburg, MD 20899, USA
[c] Associate, Engineering Laboratory, National Institute of Standards and Technology, 100 Bureau Dr, Gaithersburg, MD 20899, USA
[d] Korea Advanced Institute of Science and Technology, 291, Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea
[e] Professor Emeritus, The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-8656, Japan

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A B S T R A C T

To evaluate the environmental performance of manufacturing systems, practitioners often deploy ad-hoc methods or implement one-off solutions that are difficult to replicate in similar scenarios. Such situations can drive-up costs and cause significant delays. Hence, there is a strong need for standard methods that help describe and replicate environmental performance evaluation (EPE) processes. In response, ISO 20140 provides guidelines for converting and aggregating environmental performance evaluation data. This paper provides an overview of ISO 20140, and showcases the usefulness of ISO 20140 by describing and analyzing the usage view of the EPE process. The analysis is conducted with an evaluation experiment about the machining of a mill-tern part, in which energy consumption of a variety of process modes such as active machining, tools change, rapid traverse, and pausing, are evaluated. The experiment is jointly conducted by National Institute of Standards and Technology in the United States and the National Institute of Advanced Industrial Science and Technology in Japan.

1. Introduction

Standards play a critical role in realizing more sustainable practices in manufacturing systems. This is especially significant considering trends in digitization and virtualization of production systems. More data is being generated at unprecedented rates and variety than ever before. In response, a host of standards development activities have focused on constructing representations and methods for consistent use of data for environmental performance (Rachuri et al., 2009). For example, ASTM E3012 (ASTM E3012, 2019) provides a conceptual model for curating analytical models that estimate or predict environmental influences of manufacturing processes. However, there still remain significant challenges in identifying, constructing, and evaluating baseline metrics and performance for sustainable manufacturing (Rachuri et al., 2010). In response to these unmet needs, ISO 20140 provides guidelines for the evaluation of energy efficiency and other factors of manufacturing systems that influence the environment.

Akin to other standards, ISO 20140 offers considerable flexibility with a large degree of freedom from two aspects. First, users can specify a manufacturing process as an evaluation object at an arbitrary level of a process hierarchy. Secondly, they can formulate arbitrary relationships among environmental key performance indicators (KPIs), system values, environmental influences, and process data collected from equipment constituting a manufacturing system. As a result, ISO 20140 leaves users with the difficulty of applying its protocols to a designated context. To help the users of ISO 20140, a usage guide for the standard is in preparation. Such a usage guide includes typical scenarios used by managers responsible for production system performance, engineers planning out production sequences, designers for new product system installations, and foremen responsible for carrying out fabrication. Moreover, a usage template is in preparation, which specifies the information to be supplied by the users and their manufacturing environment for conducting the evaluation process.

To clarify the utility and efficacy of the standardized environmental performance evaluation (EPE) process supported by the ISO 20140 usage guide and template, we take an approach learned based on the design guidelines of Industrial IoT systems. The

* Corresponding author.
E-mail addresses: wzb@nist.gov, william.bernstein@nist.gov (W.Z. Bernstein).

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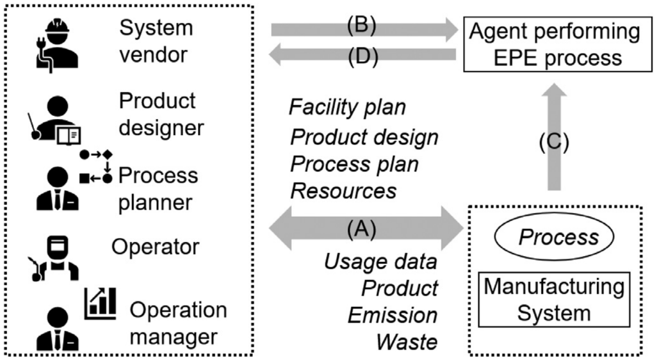

Fig. 1. Usage view of the EPE process.

guideline, also known as the Industrial Internet Reference Architecture (IIRA) (Industrial Internet Consortium, 2015) suggests designers to describe the system from business, usage, function, and implementation viewpoints. The system description from the usage viewpoint (Platform I4.0, 2018) is particularly fit to describe the concerns (and interactions) of the users of (with) the system and of other other stakeholders, which will be further analyzed with modeling and simulation techniques (Komoto and Masui, 2018).

The objective of this paper is to investigate the usage view of the standardized EPE process for various stakeholders, as illustrated in Fig. 1. In smart manufacturing environments, these stakeholders interact with manufacturing systems in order to execute a variety of manufacturing processes (see the arrows (A) in Fig. 1. In this study, an additional human / software agent that manually / automatically performs the EPE process by receiving information from stakeholders (arrow-B) and manufacturing systems (arrow-C) to eventually offer benefit through the evaluation result, such as recommendations to stakeholders concerning, e.g., a variety of design choices (arrow-D). The internal structure of the agent, i.e., the functional view that computes the results from these inputs, is out of the scope of this paper and described elsewhere (Vijayaraghaven and Dornfeld, 2010). Through this usage view, we describe the following contributions in this paper:

- Brief introduction of a usage template for reporting ISO 20140 compliant evaluation experiments.
- Clarification of the necessary inputs of the EPE process with reference to the usage template.
- Analysis of the benefits of potential stakeholders of the EPE process.
- Demonstration of practical use of the EPE process through an evaluation experiment.

To verify the description of the usage view, we are currently conducting an experiment that evaluates the EPE process by a collaboration between the National Institute of Standards and Technology (NIST) of the United States and the National Institute of Advanced Industrial Science and Technology (AIST) of Japan. In this paper, we describe the experiment from a view of users aiming at comparing process plans in the context of the machining of a mill-turn part.

The paper is organized as follows. Section 2 presents an overview of ISO 20140. Section 3 briefly introduces various types of stakeholders (users) of ISO 20140 and a description of the usage template that is used to report plans and results of a standard-compliant EPE process. Section 4 describes the usage view of an EPE process based on the evaluation experiment. Section 5 summarizes and concludes the paper.

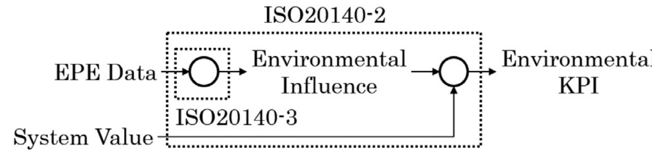

Fig. 2. The EPE process focused in ISO 20140-2 and -3.

2. Background

2.1. Interpretation of key concepts, terms, and definitions

Before describing the ISO 20140 EPE process, following the structure of the documents of the Standard, the paper first explains the key concepts, terms, and definitions. Please refer to the indicated clauses of ISO 20140 Part 2 (ISO 20140-2:2018, 2018) that describe the precise definition, scope, and characterization. This explanation in the paper complements (somewhat abstract) definitions in the documents of the Standard.

Environmental Performance Evaluation (EPE) Data (Clauses 3.1, 3.6): EPE data refer to quantities obtained from manufacturing systems (processes) necessary for the calculation of environmental influences. EPE data can be but not limited to the attributes of equipment of manufacturing systems, products to be produced, and inputs/outputs of manufacturing processes such as energy and materials. The classification of EPE data is described in ISO 20140-5 (ISO 20140-5:2017, 2017) in detail.

Environmental influences (Clause 3.3): Environmental influences are changes in physical quantities in the global environment resulting (often as by-products) from the execution of manufacturing processes under consideration. Examples include energy and material consumption, toxicity emissions, and waste. As shown above, environmental influences are derived from EPE data.

System Values (Clauses 3.8, 6): System values are physical quantities measured in terms of the primary results of the execution of manufacturing processes under consideration. Examples include the number and/or quantity of products manufactured. System values provide a basis for which environmental influences across different instances can be compared.

Environmental KPIs (Clauses 3.4, 3.5, 3.7): Environmental KPIs are used to evaluate the target processes and compare alternative designs of the target processes and/or resulting products. As shown above, they are defined by functions whose arguments are environmental influences and system values. Such KPIs are designed to allow for direct comparison across manufacturing instances.

2.2. Overview of ISO 20140

ISO 20140 standardizes the EPE process of manufacturing systems with environmental KPIs defined by environmental influences relative to a system value (ISO 20140-3:2019, 2019). The terms briefly explained above appear as the inputs and outputs of the EPE processes. ISO 20140 consists of 5 parts, of which these four parts have been recently published.

- Part 1: Overview and general principles (ISO 20140-1:2019, 2019)
- Part 2: EPE process (ISO 20140-2:2018, 2018)
- Part 3: EPE data aggregation process (ISO 20140-3:2019, 2019)
- Part 5: EPE data (ISO 20140-5:2017, 2017)

Among them, Part 2 and Part 3 describe the protocol for the EPE process and the EPE data aggregation process, respectively. The focus of Part 2 and Part 3 can be summarized by Fig. 2. The EPE process produces environmental KPIs as outputs, while it accepts EPE data and a system value as input. The EPE aggregation pro-

Table 1
Components of the usage template under development as an informative of ISO 20140.

Template component	Description
[0] General Description	Schedule, duration, and level of evaluation of manufacturing process under consideration
[1] Objective of Evaluation	Description about the objective (purpose) of environmental performance evaluation
[2] Scope of Evaluation	Specification of the target manufacturing process and conditions for EPE
[3] System Value	Physical quantity measured in terms of primary results of the execution of manufacturing processes under consideration (e.g., the number and/or quantity of products manufactured)
[4] Environmental KPI	Evaluation criteria of the target process (specified by [1]) and of alternative designs of the target processes and/or resulting products taking [3] and [5] as parameters.
[5] EPE Data	Data obtained from manufacturing systems necessary for the calculation of environmental influences
[6] EPE Data Aggregation	Calculation details of environmental influences from EPE data [5]
[7] Evaluation Calculation	Calculation details of environmental KPIs [5]
[8] Evaluation Report	Presentation of the conditions and results of environmental performance evaluation

Table 2
Description of the evaluation experiment following the usage template.

Template component	Description
[0] General Description	This experiment has been planned and conducted during 3 months between Autumn and Winter 2019 with a focus on machine tools used for machining of a test mill-turn part.
[1] Objective of Evaluation	The objective of this study is to compare the environmental performance of multiple process plans (i.e., 3-axis + 5-axis milling and turning then 5-axis milling) from two different locations (i.e., AIST and NIST) for the same mill-turn part.
[2] Scope of Evaluation	The complete machining process of a test part is the scope of evaluation. The machining of the fixtures to attach the work piece to these machining tools is out of the scope of the EPE process. The same CAD model is used as the basis of the study's evaluation conditions.
[3] System Value	Number of parts per cycle (N) [dimensionless]. N is 1 as defined by our comparison study.
[4] Environmental KPI	Cumulative energy demand over parts per cycle (E/N) [kWh per cycle]
[5] EPE Data	Energy consumption of equipment (kWh), or alternative data item such as load carried by the motors are allowed.
[6] EPE Data Aggregation	Cumulative energy demand (E) [kWh] during the target machining process is measured and its sum is calculated. In addition to the active machining mode, relevant modes such as tool change, rapid traverse, paused, waiting, warming up, cooling down, stopped (due to alarms) are included.
[7] Evaluation Calculation	As indicated in Part 2 (ISO 20140-2:2018, 2018), the KPI value is the cumulative energy demand divided by parts per cycle
[8] Evaluation Report	It will be filled after the EPE process. Whether the KPI, and other contents in the usage template are relevant for the evaluation objective should be clarified therein.

cess accepts EPE data as input and instantiates environmental influences as outputs, which is used to calculate environmental KPIs together with system values.

2.3. Usage template

The EPE process requires information from users as indicated in Fig. 1. Table 1 provides the underlying concepts of ISO 20140 as a usage template that must be instantiated to follow the standard. Table 2 provides an example instance of the usage template filled with the concrete information for the evaluation experiment that we provide in this paper.

3. The stakeholders of the standard and their role

3.1. Representative roles of potential users

ISO 20140 is intended to be used by various stakeholders, as illustrated in the left side of Fig. 1. However, the roles assigned to each of these stakeholders are inherently different. In this section, some representative roles of potential users are illustrated. Then, we clarify the particular use context of the standard.

System vendors: For system vendors who install new manufacturing systems or expand the capacity of existing manufacturing systems, the standard supports comparison of the environmental performances of equipment such as machine tools. These performances are akin to specifications (e.g., maximum energy consumption), that are independent of specific processes in the use stage of equipment.

Product designers: The standard offers the possibility for product designers to quantify the environmental performance of products, which includes the amount of wastes generated during machining. Such a performance depends on the form, features, and materials in the production stage. Note that EPE data could be synthetically generated through simulations, which is common in decision making processes during design.

Process planners: Process planners define tools and tool paths, or process plans in the form of numerical control (NC) programs, for the manufacturing of products. The standard offers the possibility for process planners to quantify the environmental performance of process plans in terms such as process time with specified product quality, e.g., surface roughness.

Operators: In the case of machine tools, operators do not only execute the NC programs, they are responsible for setting up fixtures and tool cribs before running the programs, and observing and controlling the behavior of machine tools to limit disturbances, e.g., noise and vibration. Such a control loop including the operator can be distinguished from the automated control in a machine tool. The standard offers the possibility for operators to evaluate their control operations by monitoring the energy consumption of machine tools for example, but the control behavior should be also explicitly defined.

Operation managers: With use of environmental performance criteria similar to those for operators, operation managers may be able to define the type of operators regarding environmentally friendly machining operations. Based on the evaluation of operators, operation managers can assign operators to specific machining tasks by leveraging the standard's mode definitions.

3.2. Use stages of the standard from a life cycle perspective

Based on the observation of the type of potential stakeholders of ISO 20140, the usage stages of ISO 20140 can be clarified from a life cycle perspective. First, these stages include a variety of independent life cycle stages, e.g., design, production, use, and end-of-life, of manufacturing systems. Second, it includes all stages

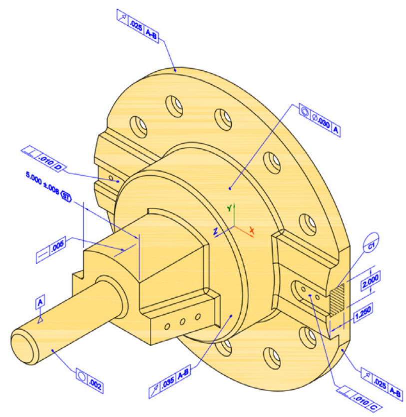

Fig. 3. NIST Product Manufacturing Information (PMI) Test Model used for the evaluation experiment (Lipman and Filliben, 2017).

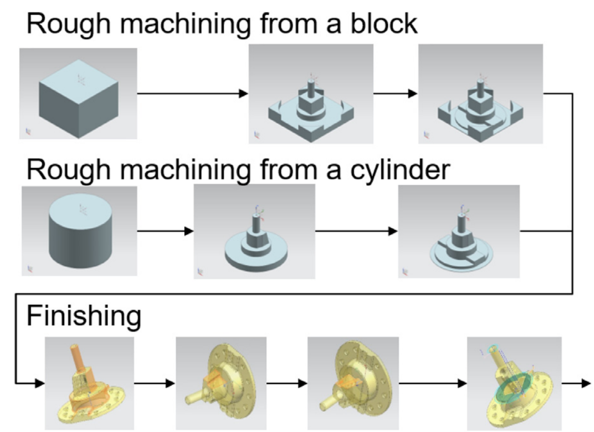

Fig. 4. Process plans in preparation.

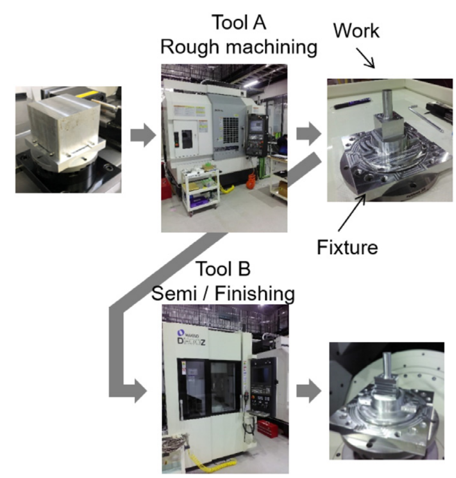

Fig. 5. Machining of a work piece (block) with two machine tools.

of the life cycle as an object of the design and analysis of product life cycles of manufacturing systems. Moreover, the standard can be applied to the production stage of products, in isolation. In other words, the environmental performance of products (produced with manufacturing systems) in the other stages of the life cycle of products can be considered outside of the scope of ISO 20140.

4. The usage view of the EPE process in context of an evaluation experiment

In this section, we describe an experiment designed for the evaluation of the EPE process by machining a test part at NIST and AIST. At NIST, we use the Smart Manufacturing Systems (SMS) Test Bed[1], a standards-based, digitally-enabled machining test bed that captures controller-based data via MTConnect. Note that the physical components of the SMS Test Bed are managed by the NIST Shops, a contract manufacturing shop akin to a small manufacturer. At AIST, we use two machining centers situated in the Cyber Physical Systems (CPS) Research Facility in AIST Tokyo Waterfront. In order to execute the EPE process for this experiment, the CAD model of the product to be fabricated and its specifications about the tolerances and dimensions are fixed. The usage template prepared for this experiment is shown in Table 2.

4.1. Test part design

We chose a solid model, shown in Fig. 3, that already serves as a test artifact (Lipman and Filliben, 2017) for testing compliance and conformance to the latest ISO 10303 standard, more commonly known as the Standard for the Exchange of of Product model data (STEP). To reduce cost and improve the manufacturability of the part, we made some small modifications, including (1) scaling the entire part by 80 % and (2) introducing a continuous radius fillet where two flat surfaces meet. The revised model and alternative process plans, which will be introduced later, are open and will be available for download.

4.2. Process planning

The process plans were developed assuming the use of machine tools available at one of the aforementioned facilities at NIST and AIST. At NIST, a machine tool with milling and turning functions (i.e., Mazak Integrex) is used for the entire machining process. The entire process plan is divided into (i) a process plan for the front side with ten cutting tools (turning, boring, and flat end-mill) and (ii) another plan for the back side with three cutting tools. At AIST, the entire process plan is divided to rough machining, semi-finishing, and finishing processes. The 3-axis machining center (i.e., Okuma M460VE) is used for the rough machining with four cutting tools, and the 5-axis machining center (i.e., Makino D200Z) is used for the other processes with eight cutting tools. Furthermore, the selection of the initial shape of work pieces influence the type of possible machining processes, the design of fixtures, and eventually the process duration. Fig. 4 shows the overview of the process plans developed at AIST. Fig. 5 showcases the physical implementation of the process plans.

In order to compare two process plans, the EPE process should be able to deal with a variation of process decomposition. In the process planning stage, the process planners can evaluate alternative process plans in terms of the number of sub-processes (including set-up, fixture changes, and tool changes), or process duration, which can be roughly estimated by experienced process planners or process simulators. Such estimations can be based on process models, mental models possessed by the planners, or digital models used by simulations, all specific to the employed machine tool.

4.3. Part manufacturing

Test workpieces with the same design are manufactured at both facilities according to their own process plans. The machine tools

[1] More information can be found at https://smstestbed.nist.gov.

Table 3
Conditions and results of the EPE experiment held at AIST.

Processes	Initial shapes	Cutting parameters	Energy demand (EI) [kWh]	Work count (SV) [Unit]	Energy Demand per Work KPI=EI/SV [kWh/Unit]
Rough Machining	Block (w100, l100, h75 [mm])	F750S2400-F600S4000, F700S2500-F500S4000	4.83 (4.49), 5.42 (4.89)	2	5.13 (4.69)
Rough Machining	Cylinder (d100, h75 [mm])	F700S2500-F400S4000	3.57 (3.45)	1	3.57 (3.45)
(Semi) Finishing	Not applicable.	F450S3250, F360S3250, F495S3250	10.33 (7.51), 7.41 (5.93), 8.41 (5.52)	3	8.71 (6.32)

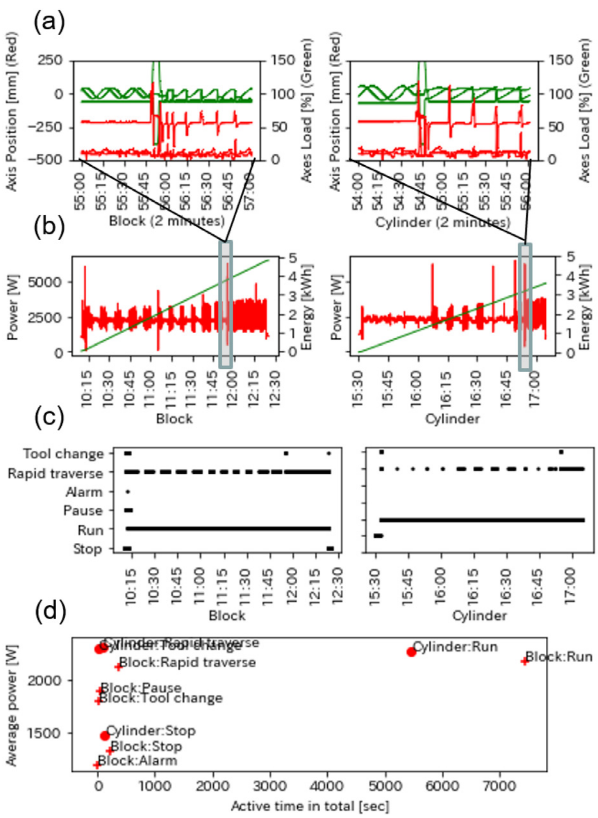

Fig. 6. Data used in the EPE process for the rough machining processes.

generate the data about their behavior outputting a variety of data items. Fig. 6 shows the data used in the EPE process for rough machining with the 3-axis machining center with different initial shapes. Specifically, Fig. 6 (a) shows the position and the applied load of each axis, which are typical types of usage data collected from the machine when a tool change occurs in the machining process. Fig. 6 (b) shows the power and energy demands monitored in the machining process, which are the EPE data for this evaluation experiment. In the EPE aggregation process, the EPE data are aggregated according to the process modes. As there is only one piece of equipment in this experiment, the mode of the machine is regarded as the mode of the process. Fig. 6 (c) shows the mode of the machine in the machining process, which includes a tool change and rapid traverses. These modes are recognized by analyzing the data as shown in Fig. 6 (a). Fig. 6 (d) summarizes the result of the EPE aggregation process regarding the modes in terms of the average power and total active time. These values define the proportion of the energy demand for a specific mode.

Table 3 shows the reference cutting conditions and results of the EPE experiment. The energy demand, the number of units, and the energy demand per unit corresponds to the environmental influence (EI), system value (SV), and KPI of this experiment ($KPI = EI/SV$), respectively. The modes other than the active machining (shown in Fig. 6 (c)) are included in the scope of the EPE process, but the score excluding these modes from the scope are also shown in brackets in Table 3. The cutting conditions are defined by the reference feed rate and spindle speed. The results show that the selection of the cylinder rather than the block as initial shape of the machining process is a good choice considering the KPI value. It is a typical recommendation to the process planners of the machining process.

5. Conclusion

ISO 20140 plays a crucial role in evaluating the environmental performance of manufacturing systems and processes, while maintaining consistency in the process for performance comparison. In order to clarify the benefits for the users of ISO 20140, this study described and analyzed the usage view of the EPE process with an evaluation experiment jointly conducted by NIST and AIST. Further study includes reporting the result of the EPE evaluation experiment following as specified by the usage template, and investigate automated decomposition of machining processes and aggregation of EPE data as specified by the usage template in terms of the behavior of machine tools.

To conclude, this experiment demonstrates that a standard template for setting up a proper evaluation process promotes communication across facilities regardless of specific installation and capabilities. Such communication is vital for properly comparing and contrasting the environmental performance of different manufacturing set-ups.

Disclaimer

Acknowledgments

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