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Standard Guide for Evaluation of Environmental Aspects of Sustainability of Manufacturing Processes[1]

This standard is issued under the fixed designation E2986; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide provides guidance to develop manufacturer-specific procedures for evaluating the environmental sustainability performance of manufacturing processes. This guide introduces decision support methods that can be used to improve sustainability performance.

1.2 The scope of this guide is constrained by the manufacturing phase of the life cycle. The guide addresses specifics related to the processes and procedures within this phase.

1.3 This guide will allow manufacturers to make effective evaluations during plant and enterprise-wide decision-making within the manufacturing phase.

1.4 This guide focuses on environmental sustainability impacts, though social and economic impacts are not explicitly excluded.

1.5 This guide addresses:

1.5.1 Setting boundaries for the evaluation of environmental sustainability of a process or processes,

1.5.2 Identifying the process and equipment-related parameters necessary for environmental sustainability-driven process evaluation,

1.5.3 Creating process models using these parameters,

1.5.4 Utilizing process models to support consistent evaluations and sustainability-driven decision-making in a manufacturing enterprise.

NOTE 1—See ULE 880 for additional guidance at enterprise-level decision-making.

1.6 This guide may be used to complement other standards that address sustainability and the product life cycle. This guide most closely relates to the inventory component as discussed in the ISO 14040 series (ISO 14040, ISO 14044) standards, efficiency as discussed in the ISO 50000 series (ISO 50001) standards, and resource management as discussed in the ISO 55000 series (ISO 55001) standards.

1.7 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E1808 Guide for Designing and Conducting Visual Experiments

E2114 Terminology for Sustainability Relative to the Performance of Buildings

E2629 Guide for Verification of Process Analytical Technology (PAT) Enabled Control Systems

2.2 *ISO Standards:*[3]

ISO 14040 Environmental management—Life cycle assessment—Principles and framework

ISO 14044 Environmental management—Life cycle assessment—Requirements and guidelines

ISO 50001 Energy management

ISO 55001 Asset management—Management systems—Requirements

2.3 *UL Standards:*[4]

ULE 880 Sustainability for Manufacturing Organizations

3. Terminology

3.1 Definitions of terms shall be in accordance with Terminology E2114.

[1] This guide is under the jurisdiction of ASTM Committee E60 on Sustainability and is the direct responsibility of Subcommittee E60.13 on Sustainable Manufacturing.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

[4] Available from UL, 333 Pfingsten Road, Northbrook, IL 60062-2096, http://www.ul.com.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *indicator, n*—quantitative value or qualitative information derived from a set of parameters that provides information about the state of a phenomenon.

3.2.1.1 *Discussion*—An example of a common indicator is CO_2 equivalent emissions.[5]

3.2.1.2 *Discussion*—An indicator can be used as a reference for decision-making.

3.2.1.3 *Discussion*—This definition is consistent with the definition in Terminology E2114.

3.2.2 *manufacturing resource, n*—any equipment, personnel, fixtures, gages, tooling, external accessories, software and control programs, and required operational settings used in manufacturing a product.

3.2.3 *metric, n*—measurable quantity on which processes are evaluated and/or compared.

3.2.3.1 *Discussion*—For instance, CO_2 equivalent emissions in metric tons or total energy consumption in kWh. Metrics provide a measure for which indicators can be evaluated.

3.2.4 *process model, n*—structured representation of the information associated with a manufacturing process.

3.2.4.1 *Discussion*—See Guide E2629 for process models specific to material use.

3.2.5 *unit manufacturing process, n*—equipment and associated operations that provide fundamental manufacturing functionality for making or modifying a part, assembly, or product.

3.2.5.1 *Discussion*—The unit manufacturing process may consist of one or more tightly integrated operations yet further decomposition of process functionality would compromise the accuracy and application of the model.

4. Significance and Use

4.1 This guide provides a reference to the manufacturing community for the evaluation of environmental sustainability aspects of manufacturing processes. This guide is intended to improve efficiencies and consistencies of informal methods by providing procedures for consistent evaluations of manufacturing processes.

4.2 This guide describes a procedure to identify parameters and models for evaluating sustainability metrics for a particular process. Users of this guide will benefit from insight into the sustainability implications of selected processes as well as the contributing factors.

5. Method for Manufacturing Process Evaluation

5.1 To evaluate the sustainability of manufacturing processes for improvement, organizations need to develop and implement a consistent, organization-wide sustainability measurement process. The following sections provide guidelines for such a process.

5.2 *Setting Sustainability Objective:*

5.2.1 Sustainability assessment starts with a statement of the sustainability goals, including the area of opportunity to be addressed. In this step, an organization identifies the opportunities from several perspectives: organizational, environmental, external and internal stakeholders.

NOTE 2—To define the objective(s), various methods for data collection and analysis can be used, such as interviewing managers, sustainability auditors, the study of past sustainability reports of the organization, or various external guidelines.

5.3 *Identifying Indicator:*

5.3.1 Indicators provide a context to measure, analyze, and score the sustainability aspects of manufacturing processes. Indicators can be defined internally, or can be selected from various indicator repositories.

5.3.2 Indicators are selected based on the sustainability objective, such as energy consumption for efficiency or CO_2 equivalent emissions for climate considerations. Factors that may influence indicator selection include the type of product, type of process, type of resource, quantity of resource, final reporting format, budget, approvals required, market, time availability, or other external guidelines.

5.3.3 An indicator is characterized by the following attributes:

5.3.3.1 *Name*—The word(s) for the distinctive designation of an indicator.

5.3.3.2 *Definition*—The statement expressing the essential characteristics and function of an indicator.

5.3.3.3 *Measurement Type*—The type of an indicator (quantitative or qualitative).

5.3.3.4 *Unit of Measure*—The unit value of the indicator.

5.3.3.5 *References*—Citable documents of existing indicator set(s) or specific indicator(s), based on which an indicator is adopted from existing set(s) or newly developed.

5.3.3.6 *Application Level*—The level in a hierarchical organization at which the indicator is applied.

5.3.4 Using this information, an organization may also set up their own sustainability indicators based on their business strategies.

5.4 *Identifying Process(es):*

5.4.1 Process identification establishes the specific process or set of processes that contribute to the identified indicator.

5.4.2 Process identification should be guided through the set objectives and the associated indicators selected.

5.4.3 The process or set of processes under evaluation should fall within the governing process or production plan. The order in which a process is selected or an objective is determined will vary depending on the production plan and organizational goals.

5.4.4 Relevant documentation should be collected and may include:

5.4.4.1 Engineering drawings.

5.4.4.2 Routing sheets with several processes.

5.4.4.3 Safety data sheets.

5.4.4.4 Quality control plans that provide product and process specifications.

5.4.4.5 Setup sheets for individual machines. Setup sheets include the operating parameters of the machine.

[5] An explanation of CO_2 equivalent emissions and an overview of common repositories can be found here: http://www.mel.nist.gov/msid/SMIR/index.html. Some common repository examples include: Global Report Initiative (http://www.globalreporting.org), Environmental Indicators for European Union (http://www.eea.europa.eu/data-and-maps/indicators).

5.5 *Identifying Evaluation Metrics:*

5.5.1 Evaluation metrics associate the process or processes to be evaluated with the identified indicator. Metrics provide a measure for which indicators can be evaluated.

5.5.2 Evaluation metrics are dependent on the selected indicator (example: waste for material efficiency and energy usage for energy efficiency), the equipment and processes being evaluated, and the availability of data.

5.5.3 Evaluation metric identification should take into consideration the capabilities and limitations of available measurement equipment.

NOTE 3—Identifying the appropriate metric is important, as the metric may influence the boundary conditions of the evaluation process and the uncertainty of the results.

5.6 *Setting Boundary Conditions:*

5.6.1 Boundary conditions limit the scope and constrain the extent of the evaluation. Boundary conditions may include the physical boundaries associated with identified equipment or time-related boundaries. Physical boundaries may be refined depending on the definitions of the unit manufacturing processes. Time-related boundary conditions establish the period of time for which measurements are taken or evaluation results are valid.

5.6.1.1 The production plan associated with the process or processes of interest will outline and establish the boundaries. Boundaries of the evaluation may be set at the supply chain, the company, the plant level, or within the plant at the manufacturing process level.

5.6.1.2 A manufacturing process can be described as a system that consists of multiple subprocesses within the boundaries. A simple boundary example consists of a single unit manufacturing process and the designated manufacturing equipment.

5.6.1.3 An example boundary application on a system is the assembly of a hand-held power tool. The boundary will determine how the unit is characterized, for instance, a boundary may be placed around the entire assembly process for the power tool, or the boundary may be placed around a subassembly of the power tool.

5.6.2 *Establishing Process Boundaries:*

5.6.2.1 The production plan may include handling and storage activities associated with the production process, thus including the peripheral equipment and storage facility. Examples include the material handling systems used to transport work-in-process (WIP) between manufacturing processes, the racks and storage for WIP and inventory, and a portion of the heating and cooling of the facility. The organization may choose not to include the peripheral equipment and storage facility in the study.

5.6.2.2 Examples of boundary conditions that should be considered:

(a) Upstream and downstream information from the supply chain.

(b) Materials handling between processes.

(c) Allocation of energy consumption in the facility (for example, heating, ventilation, and air conditioning-HVAC).

(d) Impact of peak versus off peak energy consumption.

(e) Process monitoring at the machine level.

5.6.2.3 Indicators and corresponding metrics will influence how boundary conditions are defined. For example, when evaluating for material efficiency, boundary conditions may be affected by considerations such as use of co-products, by-products, reworked, recycled or scrap material. When evaluating for energy efficiency, considerations may include cogeneration, alternate sources of energy, energy audits, or reclamation of waste energy from processes (that is, using exhaust heat from one process as energy input for a different process).

5.6.3 *Establishing Unit Manufacturing Processes:*

5.6.3.1 The identification of unit manufacturing processes will (*1*) determine where measurements should be taken in order to calculate process-specific metrics, and (*2*) provide boundaries for analytical models that can be developed using well-defined unit manufacturing processes.

5.6.3.2 Production processes can consist of multiple unit manufacturing processes. In these scenarios, the sustainability performance of a manufacturing process can be evaluated as an aggregation of the performance of unit manufacturing processes. The unit manufacturing processes identified within the established boundary conditions should either directly or indirectly relate to the chosen indicator.

5.6.3.3 Examples of boundary conditions that should be considered at the unit manufacturing process level include:

(a) Identifying useful energy, that is, the energy consumed in making the part or product.

(b) Incorporating waste heat generated during processing.

(c) Distinguishing material removed from a part or product as waste or recycled.

(d) Evaluating sub-processes within the process at efficiencies other than 100 % efficient.

5.6.4 *Supply Chain Considerations:*

5.6.4.1 Production planning may consider manufacturing resources outside of the plant through an established supply chain. The boundary conditions of the supply chain must be carefully considered. Resource data can be collected from outside plants along the supply chain.

5.6.4.2 It is possible to include external data from downstream and upstream processes, that is, consideration of the emissions associated with the electricity used by the processes.

5.6.4.3 It is important that wherever boundaries are created that they remain consistent throughout the evaluation process.

5.7 *Identifying Input and Output Parameters:*

5.7.1 Each unit manufacturing process has one or more input and output parameters associated with it. Input parameters are those parameters that feed into the process. Output parameters are those parameters that can be used to calculate the indicators used to evaluate manufacturing sustainability.

5.7.2 Input and output parameters may be associated with materials, energy, or intermediate products used to manufacture a product and produce other non-product outputs, by-products, and other non-product substances and emissions that result from a manufacturing process.

5.7.3 Input and output parameters for processes are provided in documentation such as engineering drawings, routing plans or schematics, setup sheets, and quality control plans.

5.7.4 Parameter values can be measured, estimated, or calculated. Data collection techniques are important when measuring the inputs and outputs (See 6.2).

5.8 *Creating a Process Model:*

5.8.1 Process models are used to represent a process or set of processes. Process models can include the required analytics to support repeatable evaluations of a manufacturing process.

NOTE 4—Process models may be empirical or theoretical. A process model may include, or be aggregated of, both empirical and theoretical models.

5.8.2 When creating a process model, the information and analytics that describe the manufacturing processes often differ depending on operational modes and conditions (for example, high and low speeds). Empirical models developed to simulate any process could consider such differences or be described otherwise.

5.8.3 An input-process-output model (Fig. 1) relates input and output metrics, and their unit of measure (UOM), for each process in the production plan.

5.8.4 The input and output parameters of the process model will correspond with those identified as input and output parameters when establishing the boundaries of the system. The input and output parameters of a process model will be a combination of the input and output parameters associated with the boundaries of the system, the input and output parameters of other unit manufacturing processes within the system, and the indicator for which the system is being evaluated.

5.8.5 Once necessary system parameters have been determined, and the analytical models for the manufacturing process identified, an input/output process model can be developed. The resulting process model will allow for a repeatable evaluation of the manufacturing process for the identified sustainability metric.

5.8.6 A composite process model may be formulated by aggregating multiple process models through interfaces, so that process structure, data, relationships, and resource flows can be represented. Modular, flexible, extensible, and reusable model designs are characteristics that support the effective formulation and composition of complex process models.

6. Evaluation Procedure for Sustainable Improvement

6.1 *Data Collection:*

6.1.1 A data collection plan is developed according to the objective of the evaluation. The plan includes (*1*) identifying the process information and related documents, (*2*) developing a data collection template, and (*3*) collecting sustainability data using the specified data collection method in 6.2. Reuse earlier identified documents when applicable.

6.1.2 Data collection methods are influenced by the metrics used to calculate the desired indicator, the boundaries of the system, the unit manufacturing process boundaries, and the input and output parameters identified as part of the process model. The accuracy of the evaluation results is highly dependent on the methods with which data is collected.

NOTE 5—The data content, units, and formats can lead to specific requirements during model development and evaluation. For example, a what-if analysis (7.4) requires sets of input data for the computation and comparison of alternatives, while an optimization requires parameters and data for mathematical expressions.

6.2 *Data Collection Methods:*

6.2.1 Data collection can be performed at different levels of granularity for a given range of metrics. Different scales used include: nominal scale, ordinal scale, interval scale and ratio scale.

NOTE 6—See Section 8 Scaling Methods in Guide E1808 for further clarification. The scale will depend on the level at which the evaluation is needed: factory, production plan, workstation, machine, or machine component level. The methods chosen for data collection may vary depending on factors such as desired scale, equipment, resources, and desired degree of certainty. The data collection method chosen will influence the overall uncertainty of process model results.

6.2.2 Different types of measurement methods include:

6.2.2.1 Direct measurement method: In this method, the parameter measurement is taken directly from a source machine or component.

6.2.2.2 Theoretical computation method: In this method, the parameter is calculated based on physical equations, such as those used in characterizing process models.

6.2.2.3 Estimation method: In this method, measurements are taken at a scale more abstract than the target. With estimates, care must be taken to account for outside influences.

6.3 *Data Collection Templates:*

6.3.1 Data collection templates provide structure to data collection methods. They can be used to provide consistency between metrics, process models, machines, and factories. Templates provide a format for data collection, documentation, and storage. (See Table 1.)

6.4 *Evaluating for Indicator:*

6.4.1 To determine output parameter values in a process model, appropriate data such as initial conditions, process settings, and process parameters are input into the empirical and theoretical equations. The results will provide the metrics on which the sustainability indicators can be calculated.

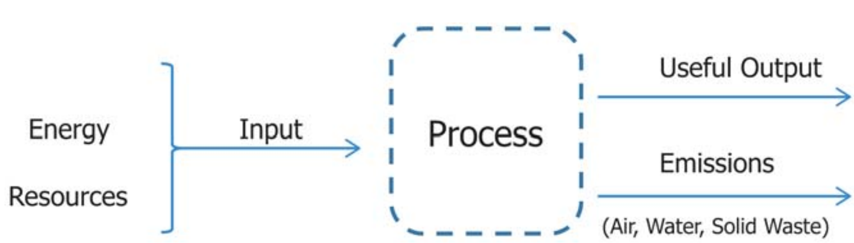

FIG. 1 Generic Input-Process-Output Model

TABLE 1 Sample Data Collection Template

Op#	Process	Machine#	energy_in kWh	energy_out kWh	material_in kg	material_out kg	chips kg
10	compact	1					
20	sinter	2					
30	machine	3					

6.5 *Establishing Target Values and Baseline:*

6.5.1 Any evaluation should require target values. A target value is a specified value that the process or product strives to meet, along with a specification of the acceptable uncertainty.

6.5.2 Target values are often set relative to established baselines. In establishing a baseline, reference data is often used. Reference data has different sources. Common sources include company-specific data under normal operating conditions, industry sector-specific data, and trade association-specific data.

6.6 *Decision-Making Process:*

6.6.1 The analysis of data is important to evaluation because it directly influences any process-related decisions made by the organization. A number of analysis techniques including qualitative, quantitative, and statistical techniques can and should be used.

6.6.2 When making process-based decisions it is important to recognize that sub-optimal solutions can be reached if a process is isolated from the rest of a system. It is important to recognize the implications of where system boundary conditions have been set, so as not to improve a process evaluation but degrade the larger system. To avoid sub-optimal solutions the user can repeat the evaluation process with a different set of boundary conditions and reevaluate.

6.6.3 Normalization helps to understand the relative magnitude of each indicator result.

6.6.3.1 Normalization is a technique for changing impact indicator values with differing units into a common, unitless format by dividing the value(s) by a selected reference quantity. This process increases the comparability of data among various impact categories.

NOTE 7—Different methods exist for normalization of the data. Some popular methods include vector normalization[6] and linear min-max normalization.[7]

NOTE 8—Normalization may consider factors such as the selection of indicators, indicators scale, comparability of indicators, weighting methods, and aggregation methods. Understanding the implications of normalized data is important, including how and why the data was normalized, when using it to make decisions.

6.6.4 When making decisions based on data, at times it may be important to stress one set of data over another. Biased-decisions can be achieved by using weighting methods on data.

6.6.5 Weighting methods allow for prioritizing objectives when making decisions.

6.6.5.1 Some weighting methods include Pairwise comparison[8] and the analytical hierarchical process (AHP).[9]

6.6.6 Aggregation methods allow sets of data to be represented by a single value. Some aggregation methods include summation, weighted arithmetic mean, and weighted geometric mean.

7. Decision-Making Methods

7.1 This guide supports analytic evaluation methods, highlighted in 7.2 through 7.4. Execution of these methods, following the guidelines below, will provide insight for sustainability-related process decisions.

7.2 *Simulation* is the imitation of the operation of a real-manufacturing process or system over time. The act of simulating a process first requires that a model be developed; this model represents the key characteristics or behaviors/functions of the selected process. Executions of the simulation models of manufacturing processes/systems generate results for evaluation of the performance of the processes/systems.

7.3 *Optimization* is the selection of a best value (with regard to some constraints) from a set of available alternatives. An optimization problem may be maximizing or minimizing a real function by systematically choosing input values from within an allowed set and computing the value of the function and compiling results. In a typical optimization problem, the goal is to find the values of controllable parameters determining the behavior of a manufacturing process to achieve a target goal. For instance, optimization methods can be used to maximize throughput or minimize energy consumption to support manufacturing for sustainability.

7.4 *What-if analysis* allows for comparison of data by varying inputs and recording changes in results. The analysis usually relies on maintaining a steady state while incrementally changing one input parameter at a time. What-if analyses use different sets of input data for computation and comparison of alternatives.

[6] Vector normalization involves the use of unit vectors, or a vector whose unit length is one, to measure magnitude.

$$\hat{X} \equiv \frac{X}{|X|}, \qquad (1)$$

where:
$|X|$ = norm of X

[7] Min-max normalization uses the lower and upper bounds of a range for a given metric or indicator to normalize a set of measurements.

$$X_{i\ 0\ \text{to}\ 1} - \frac{X_i - X_{\text{Min}}}{X_{\text{Max}} - X_{\text{Min}}} \qquad (2)$$

[8] A weighting method that involves comparing entities in pairs and assigning greater value to one over the other, or assigning a preference.

[9] A multi-criteria decision method developed by Thomas Saaty that used a hierarchical structure to model complex problems, showing relationships of the goal, objective, and alternatives. This method leverages other weighting methods.

8. Uncertainty/Sensitivity Analysis

8.1 Uncertainty quantification is an important aspect of any evaluation for decision-making. For further guidance see related reference material.[10]

9. Documentation and Reporting

9.1 Documentation and reporting is important for creating reference material for communicating results and revisiting decisions. Effective documentation would include the scope, identification of the evaluation objective and processes evaluated, details of the procedural steps taken during the evaluation, supporting data of any evaluation results, the results themselves (including sensitivity/uncertainty), and performance metrics on which results were evaluated and decisions were made.

9.2 A sustainability measurement report may be organized using the following elements: (*1*) the statement of the purpose, objectives, and scope, (*2*) administrative data, (*3*) contextual information, and (*4*) measurement results and quantification.

[10] Such as Henrion and Morgan's "Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis," and the National Research Council's "Assessing the Reliability of Complex Models: Mathematical and Statistical Foundations of Verification, Validation, and Uncertainty Quantification (2012)."

9.3 Care must be taken to ensure appropriate interpreting, generalizing, prioritization, and application of evaluation results for making decisions. The evaluation results almost always rely on the assumptions and scenarios of the system under study. Assumptions are often based on subjective judgments, estimates, and representative data. Hence, the results must be well understood and used accordingly.

9.4 Documentation and reporting of evaluation results are often used for the following purposes:

9.4.1 Record and communicate how assumptions and uncertainty of data affect evaluation results.

9.4.2 Establish baselines for future evaluations and continuous improvement.

9.4.3 Establish reference data and targets of environmental indicators for decision-making.

9.4.4 Understand the relative impacts of manufacturing resources, processes and production systems within a plant.

9.4.5 Establish as a basis for planning and prioritizing future manufacturing sustainability initiatives and investment.

9.4.6 Apply the evaluation results as training materials and information to educate personnel on manufacturing for sustainability.

10. Keywords

10.1 environmental decision making in manufacturing; manufacturing process evaluation; sustainable manufacturing