**Designation: E3096 – 17**

# Standard Guide for Definition, Selection, and Organization of Key Performance Indicators for Environmental Aspects of Manufacturing Processes[1]

This standard is issued under the fixed designation E3096; 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 addresses Key Performance Indicators (KPIs) for environmental aspects of manufacturing processes.

1.2 This guide provides a procedure for identifying candidate KPIs from existing sources for environmental aspects of manufacturing processes.

1.3 This guide provides a procedure for defining new candidate KPIs that are not available from existing sources for environmental aspects of manufacturing processes.

1.4 This guide defines a methodology for selecting effective KPIs from a list of candidate KPIs based on KPI criteria selected from Appendix X3 or defined by users.

1.5 This guide provides a procedure for normalizing KPIs, assigning weights to those KPIs, and aligning them to environmental objectives.

1.6 KPIs of Manufacturing Operation Management activities as defined in IEC 62264-1 are out of the scope since they are specifically addressed in ISO 22400-2.

1.7 How to evaluate environmental impacts is out of the scope since it is addressed in Guide E2986.

1.8 This guide can be used to complement other standards that address environmental aspects of manufacturing processes, for example, Guide E2986, Terminology E2987/E2987M, and Guide E3012.

1.9 *This guide does not purport to address the security risks associated with manufacturing and environmental information. It is the responsibility of the user of this standard to follow practices and establish appropriate information technology related security measures.*

1.10 *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.*

1.11 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

## 2. Referenced Documents

2.1 *ASTM Standards:*[2]

E2114 Terminology for Sustainability Relative to the Performance of Buildings

E2986 Guide for Evaluation of Environmental Aspects of Sustainability of Manufacturing Processes

E2987/E2987M Terminology for Sustainable Manufacturing

E3012 Guide for Characterizing Environmental Aspects of Manufacturing Processes

2.2 *IEC Standard:*[3]

IEC 62264-1 Enterprise-control system integration–Part 1: Models and terminology

2.3 *ISO Standards:*[4]

ISO 14001 Environmental management–Requirements with guidance for use

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

ISO 20140-1 Automation systems and integration–Evaluating energy efficiency and other factors of manufacturing systems that influence the environment–Part 1: Overview and general principles

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[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 International Electrotechnical Commission (IEC), 3, rue de Varembé, 1st Floor, P.O. Box 131, CH-1211, Geneva 20, Switzerland, http://www.iec.ch.

[4] Available from International Organization for Standardization (ISO), ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, http://www.iso.org.

ISO 22400-1 Automation systems and integration–Key Performance Indicators (KPIs) for manufacturing operations management–Part 1: Overview, concepts, and terminology

ISO 22400-2 Automation systems and integration–Key Performance Indicators (KPIs) for manufacturing operations management–Part 2: Environmental performance evaluation process

2.4 *NSF Standard:*[5]

NSF/GCI/ANSI 355 Greener Chemicals and Processes Information

## 3. Terminology

3.1 *Definitions*—Definitions of terms shall be in accordance with terminology in Terminology E2114, Guide E2986, Terminology E2987/E2987M, Guide E3012, ISO 20140, and ISO 22400.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *KPI criterion, n*—a norm or characteristic of a KPI that is used to determine whether the KPI is capable of assessing an environmental aspect of manufacturing processes.

3.2.2 *KPI effectiveness, n*—a measure of how well a KPI evaluates the impact of an environmental aspect of a manufacturing process on the environment.

3.2.3 *KPI normalization, n*—a procedure to adjust KPIs on different scales to a common scale.

## 4. Significance and Use

4.1 This guide provides methods for developing environmental sustainability KPIs at the manufacturing process level.

4.2 This guide provides standard approaches for systematically identifying, defining, selecting, and organizing KPIs for determining the impact of manufacturing processes on the environment.

4.3 This guide is intended for those who need effective KPIs to assess manufacturing process performance, raise understanding, inform decision-makers, and establish objectives for improvement.

4.4 If the number of stakeholders is small and the manufacturing processes are simple, KPI developers can follow the first two steps (5.2 Establishing KPI Objectives and 5.3 Defining needed KPIs) of this guide. The steps that follow include KPI selection, normalization and weighting, and KPI organization. They can be applied to larger groups of stakeholders and more complex manufacturing processes. Users of this guide can determine the number of steps they will follow because the decision is highly dependent upon the products that they make and the processes that they use.

4.5 The guide enables the development of tools for KPI management and performance evaluation that will support decision-making capabilities in a manufacturing facility, including the development and extension of standardized data, performance information, and environmental knowledge.

4.6 Procedures outlined in this guide are intended for environmental KPIs, and they also can be applied to broader sustainability KPIs as in Guide E2986.

## 5. Procedure for KPI Definition, Selection, and Organization

5.1 This section provides a procedure to establish objectives, identify/define candidate KPIs, select effective KPIs, and organize them into a set. Fig. 1 shows a workflow chart describing the procedure to develop KPIs. The following subsections describe the activities represented in each box in Fig. 1.

5.2 *Establish KPI Environmental Objectives*—A KPI objective is a threshold of achievement to improve certain environmental aspects of manufacturing processes. An objective should (*1*) reflect environmental performance, (*2*) set a normative standard for assessment in the organization, (*3*) be operational and applicable to all stakeholders, (*4*) be quantitative and measurable, (*5*) be easy to understand and communicate, (*6*) have a specific time frame, and (*7*) respect local, state/provincial, and national policies, and international priorities. For sustainability improvements, a KPI objective will support a sustainability objective as stated in Guide E2986, 5.2 Setting Sustainability Objective.

NOTE 1—*KPI Environmental Objective Example*—Reduce $CO_2$ emission 20 % within a year in a concrete-making process.

5.3 *Identification and Definition of Candidate Environmental KPIs*—When choosing candidate KPIs, stakeholders identify the necessary metrics to address the KPI objective. Examples of metrics include, but are not limited to, energy consumption in kJ, water consumption in liters, material use in kg, emissions in metric ton, etc. These metrics can either be measured directly or estimated through physics-based equations (see examples in Notes 2 and 3). KPI developers should determine what new metrics are necessary to address the KPI objective. When a new metric is selected, KPI users should consider measurement methods (such as sensors or human input), cost to measure, and implementation time in deciding how to proceed. If applicable KPIs are available from literature sources, those KPIs can be adopted. 5.3.1 describes a procedure to identify sources of KPIs. If appropriate KPIs are not available, new KPIs may be defined. 5.3.2 describes how users can define new KPIs.

NOTE 2—*Metric Example*—Energy consumption measured with a power meter.

NOTE 3—*Physics-based Equation Example*—Energy required for a metal cutting process on a steel workpiece, such as E (cutting energy) = F (cutting force) × S (cutting speed) × T (duration).

5.3.1 *Identification of Sources of Standards and Literature for KPIs*—Candidate KPIs can be defined using available information from literature. Some examples of literature sources are in Appendix X1. Initial candidate KPIs should be developed using the format in ISO 22400-1 for ease of communication among stakeholders. Some example KPIs are described in Appendix X2.

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[5] Available from NSF International, P.O. Box 130140, 789 N. Dixboro Rd., Ann Arbor, MI 48105, http://www.nsf.org.

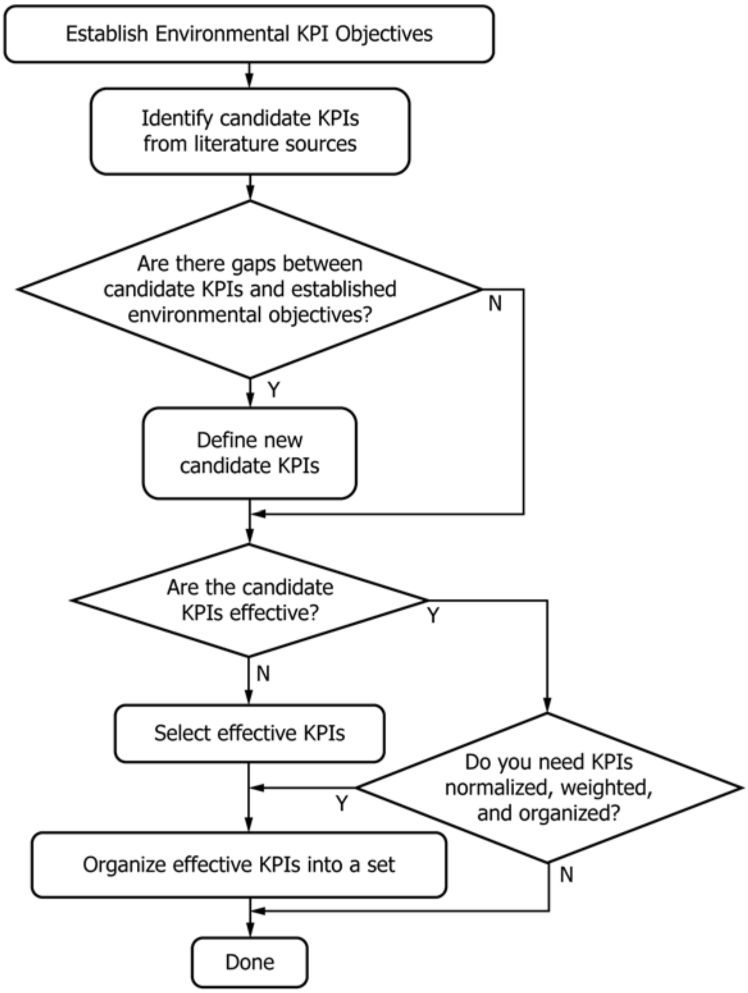

**FIG. 1 KPI Definition, Selection, and Organization Flow Chart**

5.3.2 *Procedure for Defining New Environmental KPIs*—If applicable KPIs cannot be found in literature sources or Appendix X2, new KPIs must be defined to measure environmental aspects of manufacturing processes. This procedure is described in the following two subsections (5.3.2.1 and 5.3.2.2).

5.3.2.1 *Identify Gaps in Currently Used KPIs*—KPI developers should analyze KPIs that are currently in use for the manufacturing process and identify gaps in the KPIs necessary to monitor a defined sustainability objective. If all the candidate KPIs are found in literature sources, the KPI developers can skip the step of defining new KPIs and go to the step of evaluating the candidate KPIs. If gaps are identified and KPIs that address the need cannot be found, then a new KPI should be created.

5.3.2.2 *Define New KPIs*—There are two approaches to defining a new KPI: bottom-up and top-down. The bottom-up approach starts with identifying current and necessary metrics and then assembling them into a new KPI. The top-down approach focuses on defining a new KPI and then identifying the necessary metrics to calculate that KPI. The method chosen will be based on the manufacturer's situation. The bottom-up approach is useful if addressing the improvement of a single process, and the top-down approach is driven by organizational objectives.

*(1) Bottom-Up Approach*—Once a gap is identified between KPIs currently in use and those that are needed to achieve environmental objectives, the next step is to identify metrics needed to fill these gaps. KPI developers should first focus on metrics that are already being used for the manufacturing process. If metrics are available and can address the gap in candidate KPIs, then these metrics are used in the development of a new KPI. If no available metrics address the gaps for the candidate KPIs, then new metrics must be developed. This will be addressed in the top-down approach next. The developed metrics can be arranged into a new KPI based on the KPI objectives.

NOTE 4—*Example*—If an objective is to reduce energy waste at a specific process, then measuring both total energy and energy that is needed to perform the task (necessary energy) can be used to form a KPI of energy efficiency.

NOTE 5—*Example*—KPIs could be "total energy waste = total energy – necessary energy" or "energy efficiency = necessary energy ⁄ total energy."

*(a)* These two example KPIs are formatted using the ISO 22400 template in Tables 1 and 2.

NOTE 6—*Example*—"total energy waste" provides the amount of energy that is being wasted in units of energy (kWh), and "energy efficiency" provides a percentage of necessary energy to total energy. The bounds are between 0 and 100 %, with 0 % meaning that energy is totally wasted and 100 % meaning that energy is totally converted into work. An actual energy efficiency is always less than 100 %. Both KPIs address the environmental objective of reducing energy waste; however, they may be ranked differently in importance using the procedure of selecting effective KPIs.

*(2) Top-Down Approach*—The top-down approach is driven by organizational objectives. The organizational objectives are decomposed into environmental objectives. Environmental KPIs can then be established to meet the environmental objectives. With gaps already identified in current KPIs, developers create new KPIs to meet the established KPI environmental objectives. A new KPI is created with a corresponding metric. Metrics that are currently used should be differentiated from new metrics that are used for any new KPI.

5.4 *Select Effective KPIs*—This section describes a structured approach to rank and select effective KPIs. The approach helps manufacturers define criteria for selecting KPIs and uses value functions to weigh those criteria. Those criteria are then used in the selection of KPIs. Any assumptions that experts make on creating value functions must be made clear to the decision makers. Different KPIs may create different values. More effective KPIs create more value. Fig. 2 shows a workflow chart describing the procedure to select KPIs. The following subsections will describe each box in Fig. 2.

5.4.1 *Selection Criteria*—Once candidate KPIs are identified, experts and stakeholders are enlisted to rank the KPIs based on their effectiveness at measuring improvements. Stakeholders determine a set of criteria to ensure the effectiveness of a KPI in contributing to an established sustainability objective. For example, a criterion might be selecting KPIs that are quantifiable or actionable. See Appendix X3 for additional selection criteria. The criteria are determined independently from the KPIs themselves. Stakeholders such as line managers, supervisors, and shop floor workers make their proposals for selection criteria. This information is then aggregated. A final set of criteria is obtained after additional review by the stakeholders. This final set of criteria will be applied to select KPIs.

5.4.2 *Value Function:*

5.4.2.1 Typically, criteria are not of equal weight during KPI selection. As such, experts develop a value function for each criterion. Value functions capture experts' assessment of the value of a criterion. Developing a value function starts with the definition of importance levels to be assigned to the criteria. Fig. 3 is an example of a value function for the "actionable" criterion. It has six defined levels of importance and values in the range 0 to 100. The x-axis of the function has ordinal scores correlating to possible importance levels. Subject matter experts identify the value they associate with each importance level and these are shown on the y-axis. In this case, the experts give some value to the criterion that indicates whether the work group is able to directly act on what is being measured by the KPI, that is, whether a KPI is actionable. The experts may consider the information to have some value, such as to inform other activities, but it has the most value when the work group can take action. Numerical values associated with both the importance level and the experts' evaluation of the criterion's value are represented on a graph. The shape of value functions differs depending on subject matter experts' expression of importance of a given criterion.

5.4.2.2 The shape of the graph in Fig. 3 illustrates a criterion where stakeholders must assign a very high importance level for the KPI to be of some significance in the selection process. In some situations, a given KPI, such as the use of an exotic material, may involve significant expenditure or purchase issues requiring several organizational units to be involved. Stakeholders then assign a high level of importance to the horizontal alignment criterion. Appendix X4 provides additional cases of value functions. Determining value functions is the first step towards ranking KPIs.

5.4.3 *Ranking KPIs:*

**TABLE 1 Example KPI–Total Energy Waste**

| KPI Descripiton | |
|---|---|
| Content: | |
| Name | Total Energy Waste |
| ID | |
| Description | The total energy waste measures the difference between the necessary energy (as measured by a theoretical calculation) versus the actual energy consumed by the process. |
| Scope | Process Level |
| Formula | Total Energy Waste = EC–NE<br>where EC = energy consumed in kWh<br>where NE = necessary energy in kWh |
| Unit of Measure | kWh |
| Range | Min: 0<br>Max: process dependent |
| Trend | The lower, the better |
| Context: | |
| Timing | Periodically |
| Audience | Operator, Supervisor, Management |
| Production Methodology | Discrete, Batch |
| Notes | The total energy waste provides insight into how much energy waste is being consumed at a process. It compares the energy needed at a process to the actual energy consumed. |

**TABLE 2 Example KPI–Energy Efficiency**

| | KPI Descripiton |
|---|---|
| Content: | |
| Name | Energy Efficiency |
| ID | |
| Description | The energy efficiency measures the energy efficiency of a process as compared to the theoretical necessary amount of energy needed to perform an operation. |
| Scope | Process Level |
| Formula | Energy Efficiency = NE/EC<br>where EC = energy consumed in kWh<br>where NE = necessary energy in kWh |
| Unit of Measure | % |
| Range | Min: 0 %<br>Max: 100 % |
| Trend | The higher, the better |
| Context: | |
| Timing | Periodically |
| Audience | Operator, Supervisor, Management |
| Production Methodology | Discrete, Batch |
| Notes | The energy efficiency gives insight into the theoretical amount energy necessary to perform an operation as compared to the consumed energy. |

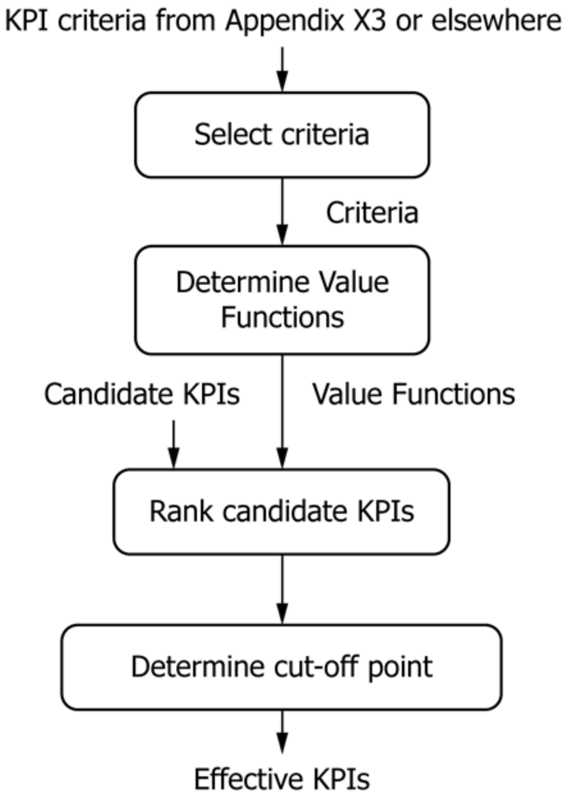

FIG. 2 KPI Selection

5.4.3.1 Next, for each KPI in the candidate set, stakeholders independently assign an importance level for all the criteria. A value is obtained from the value function for each importance level assigned. An average is calculated for the values obtained from all stakeholders for each criterion for each KPI. The final value of the importance of a KPI depends on values obtained for all the criteria. Many algorithms exist for calculating this final value. One simplified method is to calculate the total sum of values obtained from all the criteria. Ranking of KPIs is based on the final aggregated value of a KPI relative to that of other candidate KPIs.

5.4.3.2 The average value function for criteria $i$ from all stakeholders can be represented as $v_i(x_i)$. If $n$ is the number of criteria, then the final value (or aggregated value) of a KPI's importance is:

$$\text{Aggregated value} = \sum_{i=1}^{n} v_i(x_i) \qquad (1)$$

5.4.3.3 This average reflects how important the KPI is to the target manufacturing processes based on that criterion. The final rating of a KPI is the total sum of the average values obtained from all the criteria.

| Importance Level | Level | Value |
|---|---|---|
| Not Important | 0 | 0 |
| Somewhat Important | 1 | 2 |
| Fairly Important | 2 | 5 |
| Important | 3 | 12 |
| Very Important | 4 | 35 |
| Extremely Important | 5 | 100 |

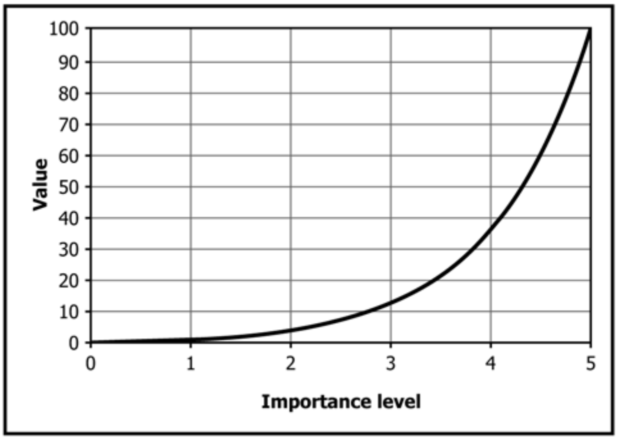

FIG. 3 Example Value Function

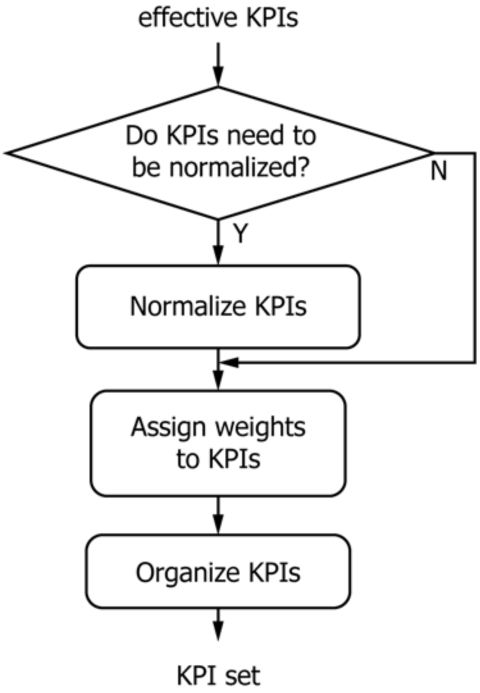

FIG. 4 KPIs Organization

5.4.3.4 Ranking of KPIs is based on the final value of a KPI's rating relative to that of other candidate KPIs. The KPI with the highest final rating ranks first, and the KPI with the lowest final rating ranks last.

5.4.4 *KPIs Selection*—Once the KPIs are ranked, only those that are ranked above a certain value are selected and included into a KPI set. This value is determined by stakeholders and is called the cutoff point.

5.5 *KPIs Normalization and Weighting*—Normalization transforms KPIs so that they can be compared on the same scale. In the scenario where KPIs have to be expressed on absolute scales, then normalization should not be performed. Weighting involves assigning relative importance based on a KPI's contribution to the environmental objective. Fig. 4 shows a workflow chart, describing the procedure to organize effective KPIs into a set. The process of organizing KPIs will be described in 5.6.

5.5.1 *KPI Normalization*—Any environmental objective may result in more than one KPI, with each KPI having a different unit of measurement. If the KPIs need to be aggregated, normalization is necessary. Normalization is the process of equating measurements from different units relative to a norm so that they can be aggregated or compared, or both. There are different approaches to normalization, as described in Appendix X5.

5.5.2 *KPI Weighting*—After normalization, weights can be assigned to the KPIs. If KPIs' objectives have the same importance in contributing to the sustainability objective, the

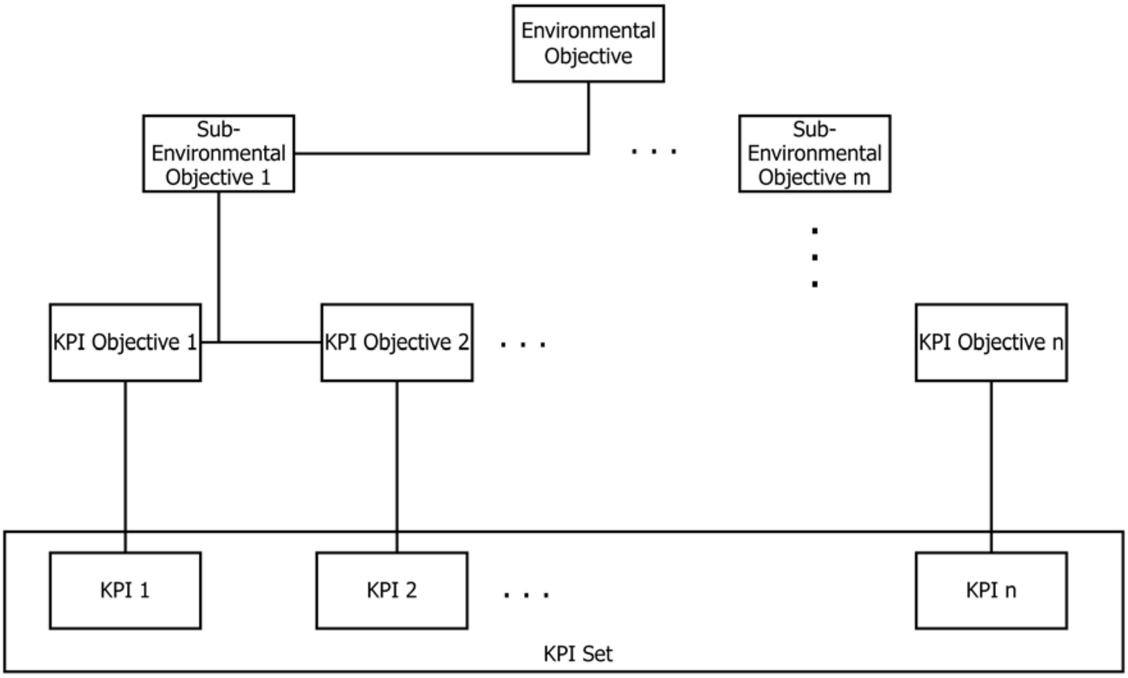

FIG. 5 Hierarchical Structure for KPI Objectives

same weight is assigned. Typically, different weights are assigned to different KPIs. The more important the KPI is, the more weight is assigned. The importance of a KPI can be determined by the total value of the KPI in the selection process (5.4.3) if weights are not assigned by stakeholders or subject matter experts. The assigned weights are dimensionless. Appendix X6 provides some additional methods for weight assignment.

5.6 *KPIs Organization*—The selected, normalized, and weighted KPIs are individual, not in a set. They must be organized into a KPI set and related to the environmental objective, as defined in 5.2.

5.6.1 *KPIs and Organizational Levels*—The selected KPI set should address the individual KPI objectives, as well as higher level environmental objectives. The relationships between KPI objectives, environmental sub-objectives, and an overall environmental objective are expressed using the hierarchical structure as illustrated in Fig. 5. KPI objectives are at the bottom while the environmental objective is set at the organizational (top) level. Environmental sub-objectives lie between the environmental objective and KPI objectives. Environmental sub-objectives are the targets for specific categories such as energy use or $CO_2$ emissions. KPI objectives outline what needs to be done to achieve these environmental sub-objectives.

5.6.2 *Environmental Objective - KPI Objective Structure:*

5.6.2.1 The hierarchical structure represents two approaches relevant for defining KPIs. The first approach starts with an environmental objective, which is decomposed into environmental sub-objectives until KPI objectives are identified. KPI objectives guide the determination of KPIs.

5.6.2.2 The second approach is to survey stakeholders to determine candidate KPIs. Candidate indicators are ranked using the method described in 5.4.

5.6.2.3 The hierarchical structure also helps to identify responsibility for actions undertaken at each control level within the organization to achieve an environmental objective. Using this structure, KPIs are used to monitor manufacturing processes so that assessments can be made to determine whether a process meets an environmental objective.

## 6. Keywords

6.1 environmental indicator; key performance indicator; KPI criteria; KPI selection; manufacturing process; value function

# APPENDIXES

## (Nonmandatory Information)

## X1. EXAMPLE SOURCES FOR DEVELOPING KPIs

X1.1 Many sources provide information that can be used for developing environmental sustainability indicators, such as the Organization for Economic Cooperation and Development (OECD), United Nation Commission on Sustainable Development, consulting companies, and numerous other local, national, and international efforts. The sources in Appendix X1 are examples. KPI developers are not required to use any of the example sources. These sources should be used as reference only.

X1.1.1 *The Global Reporting Initiative (GRI)* is a voluntary sustainability reporting initiative for organizations. The GRI consists of indicators that are identified within the three main categories of sustainability: economy, environment, and society. Each category has many aspects. The indicators defined in the environmental aspect are relevant for analysis and evaluation.[6]

X1.1.2 *The Dow Jones Sustainability Indexes (DJSI)* assesses corporate sustainability in the financial and sustainability performance of the top 10 % of the companies in the Dow Jones Global Total Stock Market Index. Assessment criteria are in the three main sustainability categories (economy, environment, and society). There are many environment criteria (for example, biodiversity, climate change governance, and footprint) for evaluating the performance of a company.[7]

X1.1.3 *The Environmental Performance Index (EPI)* was developed by the Yale Center for Environmental Law & Policy for measuring and assessing the policy performance of countries in reducing environmental stresses on human health, enhancing ecosystem vitality, and sustaining natural resource management by evaluating environmental stewardship for regions and countries. The EPI is a single value index that can be either on an environmental aspect or an environmental stress.[8]

X1.1.4 *The Organization for Economic Cooperation and Development (OECD) Sustainable Manufacturing Indicators* are a part of a toolkit and were designed for monitoring environmental conditions for sustainable development of member countries. There are 18 indicators on inputs, operations, and products for assessing manufacturing operations, including resource usage and the product as an output.[9]

X1.2 In addition to indicators and indices, databases that can be used for life cycle impact assessment exist. Many data fields in the databases capture data on assessing environmental impact and can be used to develop KPIs.

X1.2.1 *The IMPACT World+* is a life cycle impact assessment methodology[10] with the implementation of a combined assessment. In its life cycle inventory, a set of indicators (for example, Eco-indicator 99) to assess negative impact on the environment from manufacturing processes is available. Some specific metrics and indicators can be used for defining a KPI.[11]

X1.2.2 *The Intergovernmental Panel on Climate Change (IPCC)* published indicators of climate change with which we can measure impacts of greenhouse gas emissions. Related indicators in IPCC reports are on GHG emission levels.[12]

X1.2.3 *The ReCiPe* provides a life cycle impact assessment methodology. ReCiPe comprises a category of environmental indicators.[13]

X1.2.4 *TRACI 2* is an impact assessment method and software tool. It contains a database focused on the impact of chemical substances on the environment. The method is based on ISO 14044. The tool contains classification impact categories and calculation of impact category indicator.[14]

X1.2.5 *The U.S. Life Cycle Inventory (USLCI)* Database provides manufacturers with gate-to-gate, cradle-to-gate and cradle-to-grave analysis for the energy and material flows into and out of the environment in a factory producing a material, component, or assembly in the U.S. The database defines environmental aspects (as data types) that can be used to develop KPIs.[15]

X1.2.6 *The European Reference Life Cycle Database (ELCD)* has a life cycle inventory database on materials, energy, and waste generations from the operations of major companies in Europe. Environmental aspects (defined as data types and categories) in the database are sources for developing KPIs.[16]

X1.2.7 *Greener Chemicals and Processes Information* is an ANSI standard on chemical data of products and their manufacturing processes within a chemical plant. The standard identifies environment aspects (as data types with definitions) on hazardous chemicals and can be used to define KPIs.[5]

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[6] See https://www.globalreporting.org, visited June 2016.

[7] See http://www.sustainability-indices.com, visited June 2016.

[8] See http://epi.yale.edu/reports/2016-report.

[9] See https://www.oecd.org/innovation/green/toolkit/oecdsustainablemanufacturingindicators.htm, visited June 2016.

[10] See http://www.impactworldplus.org/en/.

[11] Jolliet, O., Margni, M., Charles, R. et al., *International Journal of Life Cycle Assessment*, 8:324, November 2003, doi:10.1007/BF02978505.

[12] See http://www.ipcc.ch, visited June 2016.

[13] See http://www.lcia-recipe.net, visited June 2016.

[14] See https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci, visited June 2016.

[15] See http://www.nrel.gov/lci, visited June 2016.

[16] See http://eplca.jrc.ec.europa.eu/ELCD3/, visited June 2016.

## X2. BASELINE ENVIRONMENTAL KPIs

X2.1 This appendix has a list of baseline environmental KPIs. The environmental impacts chosen are only some examples of KPIs for environmental aspects of manufacturing processes. These KPIs are not authoritative.

**TABLE X2.1 Material Efficiency**

| KPI Description | |
|---|---|
| Content: | |
| Name | Material Efficiency |
| ID | |
| Description | The material efficiency is the ratio between the material out (MAT_out) and the material in (MAT_in) at a process for the production of a part. |
| Scope | Process Level |
| Formula | Material Efficiency = MAT_out/MAT_in |
| Unit of Measure | % |
| Range | Min: 0 %<br>Max: 100 % |
| Trend | The higher, the better |
| Context: | |
| Timing | Periodically |
| Audience | Operator, Supervisor, Management |
| Production Methodology | Discrete, Batch |
| Notes | The material efficiency provides insight into how efficiently raw material is utilized by a process. A low material efficiency means there is a lot of waste material at a specific process. |

**TABLE X2.2 Virgin Material Efficiency**

| KPI Description | |
|---|---|
| Content: | |
| Name | Virgin Material Efficiency |
| ID | |
| Description | The virgin material efficiency is the ratio between the virgin material used at a process (VMAT_in) and the total material used at a process (MAT_in) for the production of a part. |
| Scope | Process Level |
| Formula | Virgin Material Efficiency = VMAT_in/MAT_in |
| Unit of Measure | % |
| Range | Min: 0 %<br>Max: 100 % |
| Trend | The lower, the better |
| Context: | |
| Timing | Periodically |
| Audience | Operator, Supervisor, Management |
| Production Methodology | Discrete, Batch |
| Notes | The virgin material efficiency provides insight into the amount of virgin material used at a process. A low virgin material efficiency means that a high amount of recycled material is used. |

### TABLE X2.3 Carbon Dioxide Emissions Due to Electricity Consumption

| KPI Description | |
|---|---|
| Content: | |
| Name | Carbon Dioxide Emissions Due to Electricity Consumption |
| ID | |
| Description | The amount of carbon dioxide produced by the electricity consumed at the process. |
| Scope | Process Level |
| Formula | Carbon dioxide emissions due to electricity consumption = EC* GHG_CO$_2$ where EC = energy consumed in kWh; GHG_CO$_2$ = Average Greenhouse Gas Emission Factor for the state in which the factory resides.[A] |
| Units of Measure | Metric ton CO$_2$ equivalent (MtCO$_2$e) |
| Range | Min: 0<br>Max: process specific |
| Trend | The lower, the better |
| Context: | |
| Timing | Periodically |
| Audience | Supervisor, Management |
| Production Methodology | Discrete, Continuous, Batch |
| Notes | The carbon dioxide emissions due to electricity consumption will measure the environmental impact of the manufacturing process on the environmental aspect of CO$_2$.[A] |

[A] See https://www.epa.gov/energy/ghg-equivalencies-calculator-calculations-and-references.

### TABLE X2.4 Energy Per Part

| KPI Description | |
|---|---|
| Content: | |
| Name | Energy Per Part |
| ID | |
| Description | The total amount of energy consumed by a process in the production of a part. It is the total energy consumed by a process (EC) divided by the quantity of parts produced at a process (PQ). |
| Scope | Process Level |
| Formula | Energy per Part = EC/PQ |
| Unit of Measure | kWh |
| Range | Min: 0<br>Max: process specific |
| Trend | The lower, the better |
| Context: | |
| Timing | Real-time, On-demand, Periodically |
| Audience | Operator, Supervisor, Management |
| Production Methodology | Discrete, Continuous, Batch |
| Notes | The energy per part measures the energy consumed by a process per part produced. This includes waste energy and usable energy. The energy consumption can be measured through a power meter or by estimating based on specific process parameters. |

### TABLE X2.5 Energy Per Good Part

| KPI Description | |
|---|---|
| Content: | |
| Name | Energy Per Good Part |
| ID | |
| Description | It is the total energy consumed by a process (EC) divided by the quantity of good parts produced at that process (GQ). |
| Scope | Process Level |
| Formula | Energy per Good Part = EC/GQ |
| Unit of Measure | kWh |
| Range | Min: 0<br>Max: process specific |
| Trend | The lower, the better |
| Context: | |
| Timing | Real-time, On-demand, Periodically |
| Audience | Operator, Supervisor, Management |
| Production Methodology | Discrete, Continuous, Batch |
| Notes | The energy per good part measures the energy consumed by a process per good part produced. The total energy consumed by the process on bad parts can be calculated by subtracting the total energy consumed by good parts from the total energy consumed by all the parts. This includes waste energy and usable energy. The energy consumption can be measured through a power meter or by estimating based on specific process parameters. |

### TABLE X2.6 Energy Efficiency

| KPI Description | |
|---|---|
| Context: | |
| Name | Energy Efficiency |
| ID | |
| Description | The energy efficiency is the ratio of useful energy (UE) to actual energy consumed (EC). |
| Scope | Process Level |
| Formula | Energy Efficiency = UE/EC |
| Unit of Measure | % |
| Range | Min: 0 %<br>Max: 100 % |
| Trend | The higher, the better |
| Context: | |
| Timing | Periodically |
| Audience | Operator, Supervisor, Management |
| Production Methodology | Discrete, Continuous, Batch |
| Notes | The energy efficiency will examine the amount of energy that is used for product creation. This is only utilized if it is possible to measure the amount of useful energy versus the amount of waste energy. Useful energy is the theoretical minimum energy required to transform the input of the process into the output of the process. |

### TABLE X2.7 Value Added Energy Efficiency

| KPI Description | |
|---|---|
| Content: | |
| Name | Value Added Energy Efficiency (VAEE) |
| ID | |
| Description | Ratio of the direct energy consumed during production time (APTEC) to the actual direct energy consumed during unit busy time (ADEC). |
| Scope | Process Level |
| Formula | Value Added Energy Efficiency = APTEC/ADEC |
| Unit of Measure | % |
| Range | Min: 0 %<br>Max: 100 % |
| Trend | The higher, the better |
| Context: | |
| Timing | On-demand, Periodically, Real-time |
| Audience | Supervisor, Management |
| Production Methodology | Discrete, Batch |
| Notes | The value added energy efficiency measures the amount of energy consumed during production time and compares it to the energy consumed during the unit busy time. It gives a measure of the energy consumed during value added activities as compared with the total amount of energy consumed. |

### TABLE X2.8 Delay Time Energy Efficiency

| KPI Description | |
|---|---|
| Content: | |
| Name | Delay Time Energy Efficiency |
| ID | |
| Description | Ratio of the direct energy consumed during unit delays (ADETEC) to the actual direct energy consumed during unit busy time (ADEC). |
| Scope | Process Level |
| Formula | Delay Time Energy Efficiency = ADETEC/ADEC |
| Unit of Measure | % |
| Range | Min: 0 %<br>Max: 100 % |
| Trend | The lower, the better |
| Context: | |
| Timing | On-demand, Periodically, Real-time |
| Audience | Supervisor, Management |
| Production Methodology | Discrete, Batch |
| Notes | The delay time energy efficiency measures the amount of energy consumed during unit delay and compares it to the energy consumed during the unit busy time. It gives a measure of the energy consumed during unplanned activities as compared with the total amount of energy consumed. |

### TABLE X2.9 Non-Value Added Energy Efficiency

| KPI Description | |
|---|---|
| Content: | |
| Name | Non-Value Added Energy Efficiency (NVAEE) |
| ID | Ratio of the non-value added direct energy consumed to the actual direct energy consumed during unit busy time (ADEC). |
| Description | |
| Scope | Process Level |
| Formula | Non-Value Added Energy Efficiency = (AUSTEC-PUSTEC+ADETEC)/ADEC |
| Unit of Measure | % |
| Range | Min: 0 %<br>Max: 100 % |
| Trend | The lower, the better |
| Context: | |
| Timing | On-demand, Periodically, Real-time |
| Audience | Supervisor, Management |
| Production Methodology | Discrete, Batch |
| Notes | The non-value added energy efficiency measures the non-value added energy consumed during the unit busy time. Non-value added activities include the difference in planned setup time versus actual setup time and actual unit delay time. The non-value added energy consumption is the difference between the actual energy consumed during setup time (AUSTEC) and the planned energy consumed during setup time (PUSTEC) and the energy consumed during actual unit delay time (ADETEC). |

### TABLE X2.10 Rework Quantity Energy Efficiency

| KPI Description | |
|---|---|
| Content: | |
| Name | Rework Quantity Energy Efficiency |
| ID | |
| Description | Ratio of the rework quantity energy consumption (RQEC) to the energy consumed at a work unit. |
| Scope | Process Level |
| Formula | Rework Quantity Energy Efficiency = RQEC/(ADEC) |
| Unit of Measure | % |
| Range | Min: 0 %<br>Max: 100 % |
| Trend | The lower, the better |
| Context: | |
| Timing | On-demand, Periodically, Real-time |
| Audience | Supervisor, Management |
| Production Methodology | Discrete, Batch |
| Notes | The rework quantity energy efficiency measures the amount of energy consumed during the production of a part that needs to be reworked to the overall energy consumed at one work unit. |

### TABLE X2.11 Water Use Efficiency

| KPI Description | |
|---|---|
| Content: | |
| Name | Water Use Efficiency |
| ID | |
| Description | Ratio of the planned water use (PWU) to the actual water use (AWU) at a process. |
| Scope | Process Level |
| Formula | Water Use Efficiency = PWU/AWU |
| Unit of Measure | % |
| Range | Min: 0 %<br>Max: 100 %<br>>100 % possible if actual water use is less than planned water use |
| Trend | The higher, the better |
| Context: | |
| Timing | Periodically |
| Audience | Supervisor, Management |
| Production Methodology | Discrete, Batch |
| Notes | The water use efficiency measures the actual water use as compared to the planned water use at a process. This gives a measure of how much water is wasted at a work unit. |

**TABLE X2.12 Water Efficiency**

| KPI Description | |
|---|---|
| Content: | |
| Name | Water Efficiency |
| ID | |
| Description | Ratio of (the amount of consumed water (CW) – the amount of wasted water (WW)) by a process to the CW. |
| Scope | Process Level |
| Formula | Water Efficiency = (CW – WW)/CW |
| Unit of Measure | % |
| Range | Min: 0 %<br>Max: 100 % |
| Trend | The higher, the better |
| Context: | |
| Timing | Periodically |
| Audience | Supervisor, Management |
| Production Methodology | Discrete, Batch |
| Notes | The water efficiency measures the amount of necessary water (CW – WW) of a process as compared to the actual water required by a process. This gives an indication of the efficiency of using water. |

**TABLE X2.13 Treated Water Efficiency**

| KPI Description | |
|---|---|
| Content: | |
| Name | Treated Water Efficiency |
| ID | |
| Description | Ratio of the actual treated water use (ATWU) to the actual water use (AWU) at a work unit. |
| Scope | Process Level |
| Formula | Treated Water Efficiency = ATWU/AWU |
| Unit of Measure | % |
| Range | Min: 0 %<br>Max: 100 % |
| Trend | The higher, the better |
| Context: | |
| Timing | Periodically |
| Audience | Supervisor, Management |
| Production Methodology | Discrete, Batch |
| Notes | The treated water efficiency measures the actual amount of treated water as compared to the actual water use at a work unit. This gives an indication of the amount of water that is treated from a given work unit. |

## X3. EXAMPLES OF KPI SELECTION CRITERIA

X3.1 This appendix has a list of possible KPI criteria. They are examples. These example KPI criteria are not authoritative.

X3.1.1 *Aligned (Vertical)*—The degree to which a KPI is able to effect change in higher-level KPIs.

X3.1.2 *Aligned (Horizontal)*—The degree to which a KPI is aligned with KPI sets in same-level operations in the corporate hierarchy.

X3.1.3 *Quantifiable*—The degree to which a KPI can be stated numerically and precisely.

X3.1.4 *Balanced*—The degree to which a KPI is balanced within its chosen set of KPIs.

X3.1.5 *Actionable*—The degree to which a team responsible for the KPI is able to influence the value of that KPI within their own operation.

X3.1.6 *Permissible*—The authority a team has to influence the value of the KPI within their own operation.

X3.1.7 *Calculable*—The correctness and completeness of the calculation required to compute the value of the KPI.

X3.1.8 *Valid*—The equivalence between the working definition of the KPI and the standard definition, if one exists.

X3.1.9 *Support (Team)*—The willingness of team members to choose appropriate KPIs, achieve KPI targets, and perform the tasks necessary to improve target KPI values.

X3.1.10 *Support (Management)*—The willingness of plant management to support choice of appropriate KPIs, achievement of KPI targets, and performance of the tasks necessary to improve target KPI values.

X3.1.11 *Documented*—The degree to which the documented instructions for implementation of a KPI are correct, complete, and unambiguous, including instructions on how to compute the KPI, what measurements are necessary for its computation, and what actions to take for different KPI values.

X3.1.12 *Accessible/Usable*—The level of ease to obtain correct and complete KPI measurements.

X3.1.13 *Comparable*—The degree to which historic data is maintained and available for comparison to current values.

X3.1.14 *Understandable*—Team member understanding of the meaning of the KPI, particularly with respect to corporate goals.

X3.1.15 *Quality of Data*—The level of fidelity between the reported KPI value and its true value.

X3.1.16 *Time-bounded*—The degree to which a KPI is computed and accessible in real-time.

X3.1.17 *Analytically Sound*—The clarity of analysis of constituent variables and derivation of the KPI expression, that is, the KPI is well-founded in technical and scientific terms.

X3.1.18 *Policy Relevance and Utility to Users*—In line with organizational goals and should trend over time in response to changes in the operations. Should be useful for decision-making and relevant to continuous sustainability improvement.

X3.1.19 *Susceptible/Sensitive/Controllable*—The susceptibility of the KPI to change if a different policy decision is implemented, that is, can policy maker or user control the KPI?

X3.1.20 *Scalable*—The degree of scaling of the KPI to different size of the problem, that is, the quantitative values of constituent variables and data.

X3.1.21 *Reproducible and Reliable*—The degree to which the KPI can be used to produce consistent results.

X3.1.22 *Cost Effectiveness*—The degree of cost benefit implementing the KPI, that is, as dictated by data availability, skills, and other requirements.

X3.1.23 *Consensus Based*—The degree of support of the KPI from different stakeholders in the organization and agreement with other industries within the sector.

X3.1.24 *Consistency*—The degree to which the KPI is consistent with organization environmental accounting.

X3.1.25 *Comparability for External Benchmarking*—Promotion of common measurement across different industries.

X3.1.26 *Consistent with Sustainability*—The degree of consistency with the principles of sustainability assessment at the abstraction of the unit manufacturing process level.

X3.1.27 *Representative*—The degree to which the KPI represent the physical system under study as well as the key concerns of the manufacturing industry in general.

X3.1.28 *Importance*—The extent to which the KPI really represents the key aspects of sustainability of the manufacturing system and hence likely to generate the greatest impact.

X3.1.29 *Relatable*—The degree of relating the KPI to different levels of the organizational hierarchy.

## X4. EXAMPLES OF VALUE FUNCTIONS

X4.1 This appendix has a list of possible value functions. They are examples. These example value functions are not authoritative.

X4.1.1 In the cost effectiveness example (Fig. X4.1), the importance level to be assigned by a stakeholder to a criterion is divided into six levels (not important, somewhat important, fairly important, important, very important, and extremely important), corresponding to the scores 0, 1, 2, 3, 4, and 5, respectively. The Y axis (V(x)) in Fig. X4.1 shows the values that subject matter experts place on the various levels of "importance" assigned by stakeholders. For example, the subject matter expert decides that if a stakeholder rates the criterion as "Fairly Important," this has a value of 40. The value for this particular criterion is lower if a subject matter expert sets it at a lower importance level.

X4.1.2 In the relevance criterion example (Fig. X4.2), the relevance level is divided into the following seven levels: not relevant, slightly relevant, moderately relevant, fairly relevant, relevant, very relevant, and extremely relevant. The subject matter expert decides that if a stakeholder rates the criteria as "relevant," this has a value of 39.

X4.1.3 The procedure to generate a value function is to first determine and describe the discrete levels of importance of the criterion. For each importance level or score, determine the value associated with it. Then, use line or curve segments to connect values to generate a continuous function. A value function (V(x)) can also be generated by a mathematical expression derived from first principles. Once a value function is generated, it is used to determine each KPI's importance based on the selected criterion.

X4.1.4 The shape of the curve depends on the phenomenon studied. In the examples provided, there are six/seven defined discrete scores to represent importance/relevance levels.

| | | x | V(x) |
|---|---|---|---|
| **Importance Level** | Not important | 0 | 0 |
| | Somewhat important | 1 | 30 |
| | Important | 2 | 40 |
| | Fairly important | 3 | 52 |
| | Very important | 4 | 70 |
| | Extremely important | 5 | 100 |

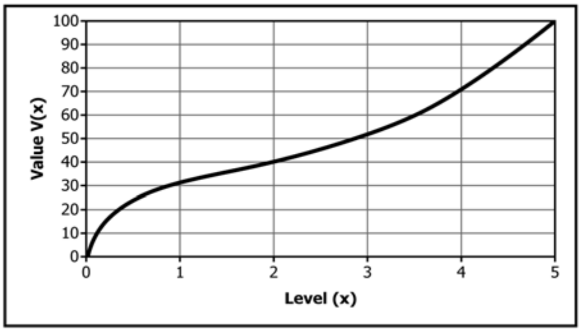

FIG. X4.1 Example Criterion: Cost Effectiveness

| | | x | V(x) |
|---|---|---|---|
| **Relevance Level** | Not relevant | 0 | 0 |
| | Slightly relevant | 1 | 3 |
| | Moderately relevant | 2 | 9 |
| | Fairly relevant | 3 | 25 |
| | Relevant | 4 | 39 |
| | Very relevant | 5 | 69 |
| | Extremely relevant | 6 | 100 |

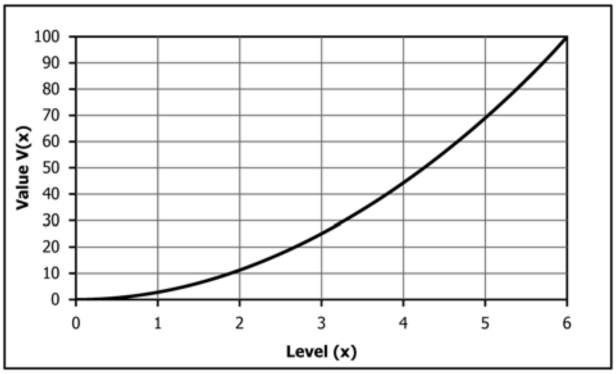

FIG. X4.2 Example Criterion: Relevance

## X5. EXAMPLES OF NORMALIZATION APPROACHES

X5.1 Normalization is a technique for transforming measured values of different units into a common and usually unitless format, for example, percentage. This process increases the comparability of data among various environmental impact categories. It also enables aggregation of the data quantities. Most studies in environmental sustainability use the reference-based normalization method where the measured value is divided by a given reference quantity. However, there are other methods of normalization that also can be employed. Common normalization methods are listed in Table X5.1. These methods are examples. They are not authoritative.

**TABLE X5.1 Common Normalization Methods**

| Normalization Approach | Definition[A] | Normalized Vector |
|---|---|---|
| Vector normalization | $n_{ij}=\frac{x_{ij}}{\sqrt{\Sigma_{i=1}^{m}X_{ij}^{2}}}$<br>i = 1,...,m j = 1,...,n for both benefit and cost variables | $0 < n_{ij} < 1$ |
| Linear max-value-based normalization | $n_{ij}=\frac{X_{ij}}{\max_i X_{ij}}$<br>i = 1,...,m j = 1,...n, for benefit variables in decision matrix with only benefit variables or both benefit and cost variables<br>$n_{ij}=1-\frac{X_{ij}}{\max_i X_{ij}}$<br>i = 1,...,m j = 1,...,n, for cost variables in decision matrix with only cost variables<br>$n_{ij}=\frac{\min_i X_{ij}}{X_{ij}}$<br>i = 1,...,m j = 1,...,n, for cost variables in decision matrix with both benefit and cost variables | $0 < n_{ij} \le 1$ |
| Linear min-max normalization | $n_{ij}=\frac{X_{ij}-\min_i X_{ij}}{\max_i X_{ij}-\min_i X_{ij}}$<br>i = 1,...,m j = 1,...,n, for benefit variables<br>$n_{ij}=\frac{\max_i X_{ij}-X_{ij}}{\max_i X_{ij}-\min_i X_{ij}}$<br>i = 1,...,m j = 1,...,n, for cost variables | $0 \le n_{ij} \le 1$ |
| Linear sum-based normalization | $n_{ij}=\frac{X_{ij}}{\Sigma_{i=1}^{m}X_{ij}}$<br>i = 1,...,m j = 1,...,n, for both benefit and cost variables | $0 < n_{ij} < 1$ |
| Non-monotonic normalization[B] | $n_{ij}=e^{-\frac{z^2}{2}},z=\frac{(x_{ij} - x_j^0)}{\sigma_j}$<br>i = 1,...,m j = 1,...,n, for benefit, cost and non-monotonic variables<br>$x_j^0$ is the most favorable value and $\sigma_j$ is the standard deviation of alternative ratings with respect to the $j_{th}$ variable. | $0 < n_{ij} < 1$ |
| Target-based normalization[B] | $n_{ij}=1-\frac{\lvert x_{ij}-T_j\rvert}{Max\{\max_i X_{ij} , T_j\}-Min\{\min_i X_{ij} , T_j\}}$<br>i = 1,...,m j = 1,...,n, for benefit, cost and non-monotonic variables<br>$T_j$ is target value | $0 \le n_{ij} \le 1$ |
| Reference-based normalization | $n_{ij}=\frac{x_{ij}}{ref_{ij}}$for each i and j, assuming $0<ref_{ij}<\infty$ | $0 < n_{ij} < \infty$ |
| Ranking[C] | $I_{qc}^{t}=Rank(x_{qc}^{t})$ | Not necessarily in the range of [0,1] |
| Standardization (or z-score)[C] | $I_{qc}^{t}=\frac{x_{qc}^{t}-x_{qc=c^*}^{t}}{\sigma_{qc=c^*}^{t}}$ | Not necessarily in the range of [0,1] |
| Distance to reference country[C] | $I_{qc}^{t}=\frac{x_{qc}^{t}}{x_{qc=c^*}^{t_0}}$(like reference-based normalization)<br>or $I_{qc}^{t}=\frac{x_{qc}^{t}-x_{qc=c^*}^{t_0}}{x_{qc=c^*}^{t_0}}$ | By the first equation $0<n_{ij}=I_{qc}^{t}\le1$<br>By the second, not necessarily in the range of [0,1] |
| Indicators above or below the mean[C] | If$I_{qc}^{t}=\frac{x_{qc}^{t}}{x_{qc=c^*}^{t_0}}>(1 + P)$then$I_{qc}^{t}=1$<br>If$I_{qc}^{t}=\frac{x_{qc}^{t}}{x_{qc=c^*}^{t_0}}<(1 - P)$then$I_{qc}^{t}=-1$<br>If$(1 - P)<I_{qc}^{t}=\frac{x_{qc}^{t}}{x_{qc=c^*}^{t}}<(1 + P)$then$I_{qc}^{t}=0$ | $n_{ij}=I_{qc}^{t}=\{0, 1, - 1\}$ |

**TABLE X5.1** *Continued*

| Normalization Approach | Definition[A] | Normalized Vector |
|---|---|---|
| Cyclical indicators (OECD)[C, D] | $I^t_{qc} = \frac{x^t_{qc} - E_t(x^t_{qc})}{E_t(\lvert x^t_{qc} - E_t(x^t_{qc})\rvert)}$<br>$E_t(x^t_{qc})$ = mean over time | Not necessarily in the range of [0,1] |
| Balance of opinions (EC)[C, E] | $I^t_{qc} = \frac{100}{N_e}\sum_e^{N_e} \mathrm{sgn}_e(x^t_{qc} - x^{t-1}_{qc})$ | $-100 \le n_{ij} = I^t_{qc} \le 100$ |
| Percentage of annual differences over consecutive years[C, D] | $I^t_{qc} = \frac{x^t_{qc} - x^{t-1}_{qc}}{x^{t-1}_{qc}}$ | Not necessarily in the range of [0,1] |

[A] $x$ = measured value; i = unit process; $j$ = key performance indicator; $n_{ij}$ = normalized vector; cost variables = desired outcome is as low as possible; benefit variables = desired outcome is as high as possible.

[B] This method can be used in the presence of target value.

[C] $x^t_{qc}$ is the value of indicator $q$ for country $c$ at the time t. c* is the reference country.

[D] This method can be used if the indicators are available for a number of years.

[E] The operator gives the sign of the argument (that is, +1 if the argument is positive, -1 if the argument is negative). $N_e$ is total number of subject matter experts surveyed.

## X6. METHODS TO ASSIGN WEIGHTS TO SELECTED KPIs

X6.1 After KPIs are selected, weights can be assigned to the KPIs to indicate their relative importance to the environmental goal. Many weight assignment methods have been developed. This appendix provides some examples of commonly used weight assignment methods. Detailed information about these methods can be found in the references below. Selecting what method to use depends on many factors, such as the company's priority in achieving the environmental goal, complexity of the process, and the number of KPIs.

X6.1.1 *Analytic Hierarchy Process (AHP) Method*—Procedure using AHP[17] for determining weights is as follows:

X6.1.1.1 Create a scale of importance, for example, 1 to 10, for comparing relative importance between a pair of KPIs to the environmental objective. Assume that there are *N* KPIs, where *N* is a positive integer.

X6.1.1.2 Develop a pairwise comparison matrix, *A*, which is an *N* by *N* square matrix. *A* should be positive, reciprocal, and consistent. Consistency is tested as follows.

X6.1.1.3 Compute the consistency ratio of the matrix according to the procedure below:

*(a)* Determine the maximum eigenvalue $\lambda_{max}$ of *A*.

NOTE X6.1—There are *N* eigenvalues in total.

*(b)* Determine Consistency Index from CI = ($\lambda_{max}$ – N)/(N-1).

*(c)* Consistency ratio is calculated using CR = CI/Index of consistency. Index of consistency is obtained from Fig. X6.1 where the upper row is the order of the matrix (*N*) and the lower row is the suggested limit of CR.

X6.1.1.4 Compare consistency ratio of the pairwise comparison matrix with what has been specified. Saaty[17] argues that CR < 0.1 means consistency. If CR is 0.9, then the pairwise comparison values are random and untrustworthy. Decision makers are asked to repeat the pairwise comparisons more carefully until CR < 0.1. The key issue is consistency. If *X* is more important than *Y* and *Y* is more important than *Z*, then it implies that *X* is more important than *Z*.

X6.1.1.5 Normalize the eigenvector corresponding to $\lambda_{max}$. The members of this eigenvector become the weights of KPIs.

NOTE X6.2—The sum of all the weights is 1 in Appendix X6. An example of using the AHP method can be found in Ocampo et al.[18]

X6.1.2 *Criterion Value Ratio Weighting Method*—From the values ($v_1$, …, $v_n$) generated in selecting KPIs, a KPI's weight can be computed as its value divided by the sum of values of all the KPIs.

$$w_i = \frac{v_i}{\Sigma_1^n v_i} \qquad (X6.1)$$

where:

$w_i$ = weight of the ith KPI, and
$v_i$ = value of the ith KPI.

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.00 | 0.00 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 | 1.51 | 1.48 | 1.56 | 1.57 | 1.59 |

**FIG. X6.1 Index of Consistency**

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[17] Saaty, T., *The Analytic Hierarchy Process*, RWS Publications, Pittsburgh, PA, 1990.

[18] Ocampo, L., Vergara, V., Impas, C., Tordillo, J., and Pastoril, J., "Identifying Critical Indicators in Sustainable Manufacturing Using Analytic Hierarchy Process (AHP)," *Journal of Manufacturing and Industrial Engineering*, Vol 14, No. 3-4, 2015, DOI: http://dx.doi.org/10.12776/mie.v14i3-4.444.

X6.1.3 *Rank-Based Weighting Methods*—Rank-based weighting methods use the knowledge of the ordinal ranking of preference without quantitative information on how much more important one KPI is relative to others. KPIs can be ranked from 1 to *N*, where 1 is the rank of the most important KPI, and *N* is the least important KPI. Two methods can be used to determine weights based on ranking.[19]

X6.1.3.1 *Rank-Order Centroid Method:*

$$w_i = \frac{1}{N}\Sigma_{k=1}^{N}\frac{1}{k} \tag{X6.2}$$

where:

$w_i$ = weight of the i$^{th}$ KPI,
$k$ = rank of the i$^{th}$ KPI, and
$N$ = total number of ranks.

X6.1.3.2 *Rank-Sum Method:*

$$w_i = \frac{N+1-i}{\Sigma_{k=1}^{N}k} \tag{X6.3}$$

where:

$w_i$ = weight of the i$^{th}$ KPI,
$k$ = rank of the i$^{th}$ KPI, and
$N$ = total number of ranks.

When multiple KPIs have the same rank, the number of KPIs, *N*, and the number of ranks, *M*, are different. The above two methods should be modified with the consideration of *N*, *M*, and the multiplicities of ranks.

X6.1.4 *Direct Assignments by Experts*—Have experts directly assign weights to KPIs. Then, share and modify assignments in an iterative manner until an agreement is reached.

X6.1.5 *Default Weighting*—The default is no weight assignment.

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[19] Jia, J., Fischer, G., and Dyer, J., "Attribute Weighting Methods and Decision Quality in the Presence of Response Error: A Simulation Study," *Journal of Behavioral Decision Making*, Vol 11, 1998, pp. 85–105.

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