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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~~ 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~~ safety, health, and ~~health~~environmental 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

[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.

***A Summary of Changes section appears at the end of this standard**

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

[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.

4.7 A quick guide on how to use this guide can be found in Appendix X7.

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

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

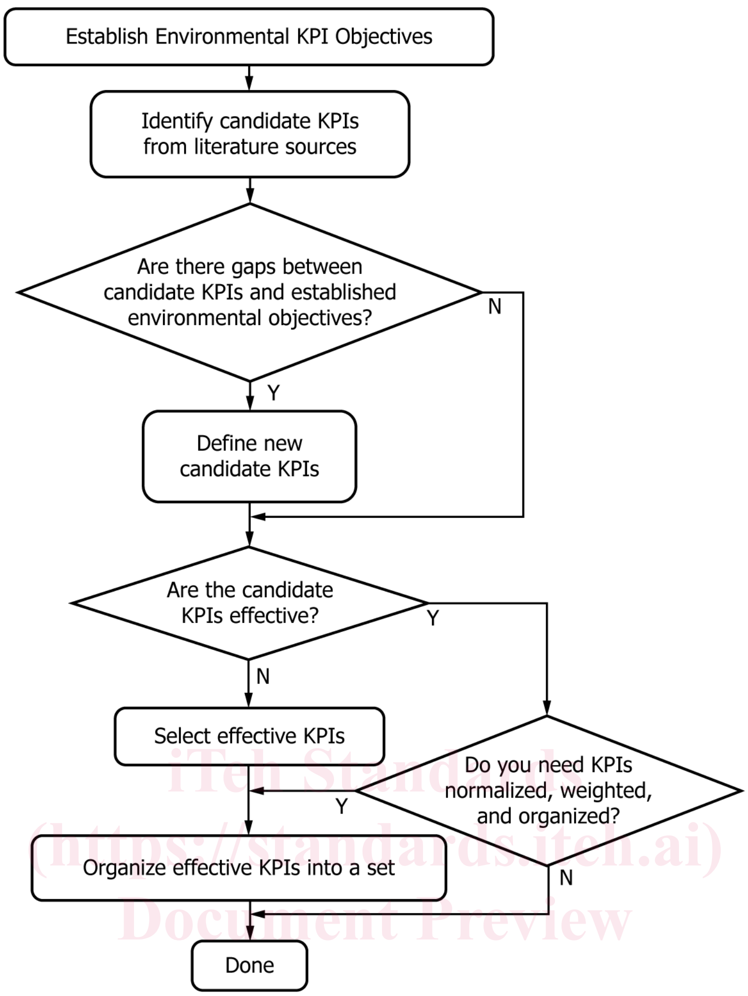

FIG. 1 KPI Definition, Selection, and Organization Flow Chart

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.

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

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 where EC = energy consumed in kWh where NE = necessary energy in kWh
Unit of Measure	kWh
Range	Min: 0 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 where EC = energy consumed in kWh where NE = necessary energy in kWh
Unit of Measure	%
Range	Min: 0 % 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.

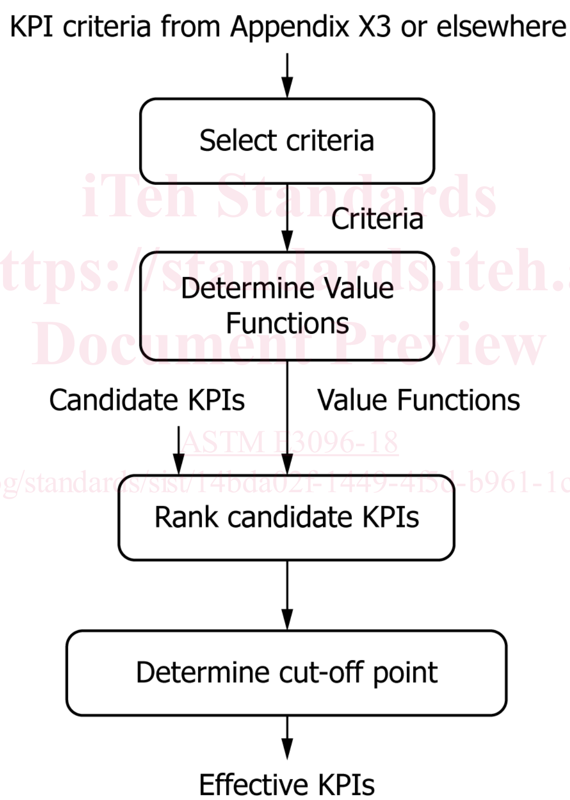

FIG. 2 KPI Selection

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

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

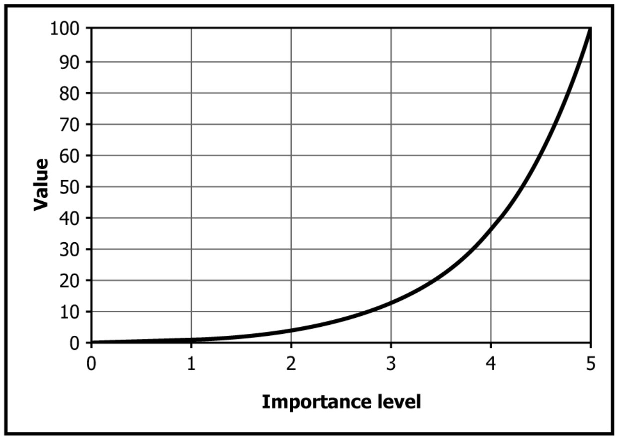

FIG. 3 Example Value Function

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:*

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:

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

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.

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 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.

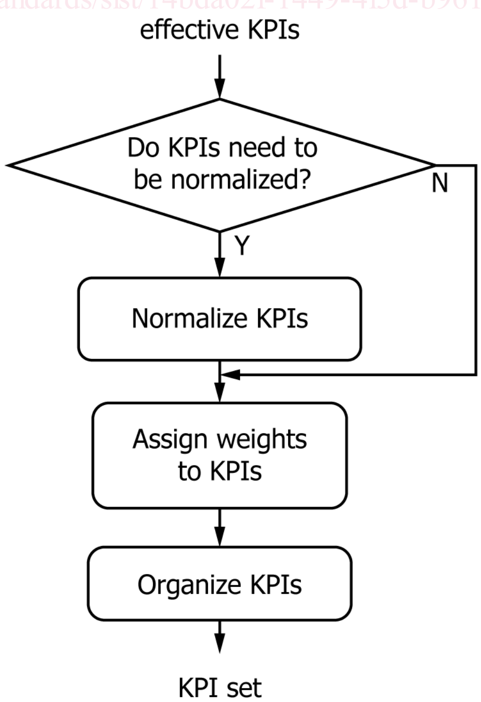

FIG. 4 KPIs Organization

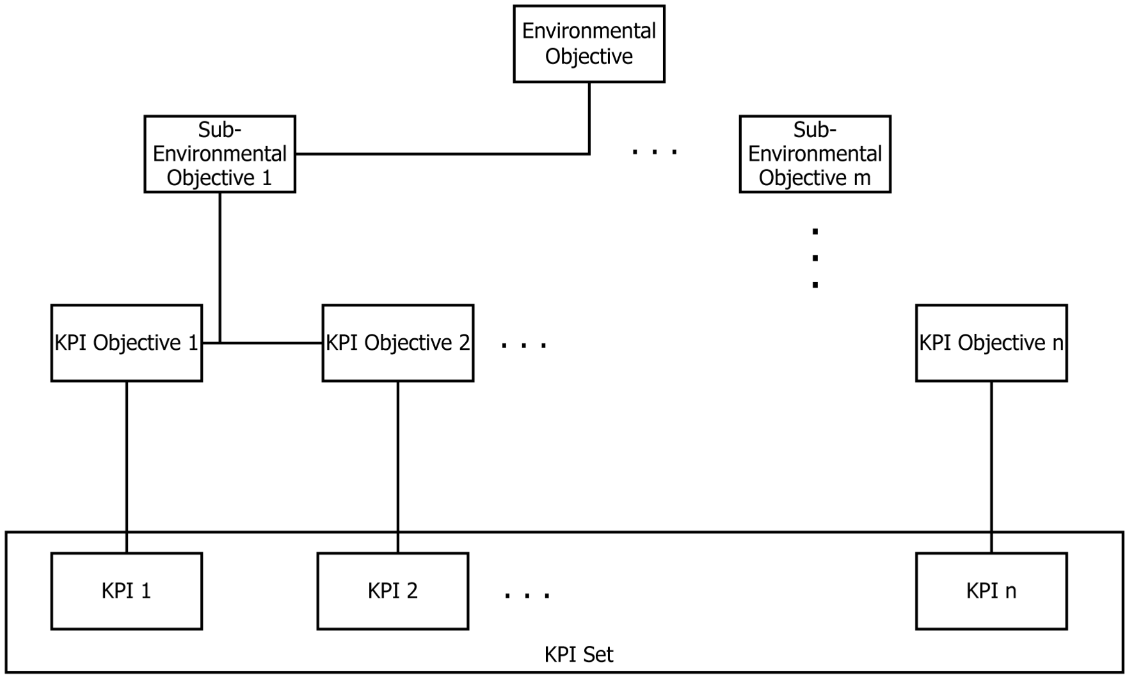

FIG. 5 Hierarchical Structure for KPI Objectives

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]

[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.~~http://epi2016.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.