Procedure for Selecting Key Performance Indicators for Sustainable Manufacturing

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ABSTRACT

The need for an open, inclusive, and neutral procedure in selecting key performance indicators (KPIs) for sustainable manufacturing has been increasing. The reason is that manufacturers seek to determine what to measure to improve environmental sustainability of their products and manufacturing processes. A difficulty arises in understanding and selecting specific indicators from many stand-alone indicator sets available. This paper presents a procedure for individual manufacturers to select KPIs for measuring, monitoring and improving environmental aspects of manufacturing processes. The procedure is the basis for a guideline, being proposed for standardization within ASTM International. That guide can be used for (1) identifying candidate KPIs from existing sources, (2) defining new candidate KPIs, (3) selecting

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appropriate KPIs based on KPI criteria, and (4) composing the selected KPIs with assigned weights into a set. The paper explains how the developed procedure complements existing indicator sets and sustainability-measurement approaches at the manufacturing process level.

Key Words: KPI Criteria, Value Function, KPI Selection, Sustainable Manufacturing

INTRODUCTION

Manufacturing companies face increasing pressure to improve the sustainability of their operations [1, 2, 3]; however, beyond reduce, reuse, recycle programs, little guidance is available to help manufacturers minimize their environmental impacts [4]. In response to the increasing pressures and as a forum for establishing responsible practices, ASTM initiated a subcommittee on Sustainable Manufacturing (ASTM E60.13).

A literature review shows that major sustainability indicators are defined for specific, individual businesses [5]. Indicators that are uniformly defined and harmonized, therefore, are largely missing. A few major indicator sets have been developed for analyzing sustainability and scoring manufacturing organizations. For example, the Organization for Economic Cooperation and Development (OECD) [6] Core Environmental Indicators (CEI) includes 46 indicators to measure the impact of industrial activities on the environment in industrialized countries. The United Nations (UN) Commission on Sustainable Development [7] identifies 96 indicators to address environmental deterioration due to human activities. The indicators are created for businesses, companies, and factories; however, few publicly-available indicator sets exist at the operational level for individual processes. Standard procedures for identifying, defining, selecting, and composing a required set of Key Performance Indicators (KPIs) for manufacturing are lacking.

This paper addresses the question of what to measure to assess environmental sustainability at the manufacturing process level. The scope includes identification, definition, selection, and composition of environmental KPIs for individual processes. It complements guidelines specified in standards such as ASTM 2986-15 [8], ASTM 3012-16 [9], ISO 22400 [10], and ISO 20140 [11]. The purpose is to provide a guide for industry to identify candidate KPIs from existing sources, define new candidate KPIs, select the most effective KPIs based on KPI criteria, and compose a final KPI set. The approach relies on both human judgment and quantitative methods. The humans are stakeholders and subject matter experts, who are aware of the activities that are important to the success of the organization.

In section 2, we review the state of the art as well as challenges for sustainable manufacturing KPI ranking. This is followed by a description of value-focused concepts and the value function approach for KPI selection. Section 3 describes the proposed procedure for defining. Section 4 shows a demonstration of the procedure with a case study. Section 5 presents a discussion and conclusion of the paper.

2 BACKGROUND AND RELATED WORK

In the past decade, there has been considerable research in sustainable manufacturing and related measurement methodologies. Haapala et al. thoroughly review concepts, tools, and methods for sustainable manufacturing [12]. Duflou et al. provide a systematic overview of energy and resource efficiency methods and techniques for discrete part manufacturing [13]. These and similar publications review and analyze methodologies for developing sustainable manufacturing practices from the enterprise level to the process level. However, assessing sustainability performance requires the availability of appropriate key performance indicators (KPIs).

2.1 Sources for sustainable manufacturing indicators

Efforts to select indicators for sustainable manufacturing have led to the establishment of best practices at the organizational level as well as lifecycle-impact-assessment methods. A best practice example is the Global Reporting Initiative, which consists of indicators to assess sustainability along three dimensions: economy, environment, and society [14]. A lifecycle assessment method example is IMPACT 2002+, which contains 14 midpoint categories mapped to four damage categories [15].

Recently, however, efforts have been made to develop other sources of indicators, indices, and frameworks for the lower control levels in manufacturing. The Lowell Center for Sustainable Production, proposed an indicator framework for shifting towards more sustainable manufacturing practice [16]. The research proposed twenty-two indicators and a guide to their application. In 2009, the National Institute of Standards and Technology (NIST) created a public repository of sustainability indicators to consolidate work of several organizations in the sustainable manufacturing area [17]. Joung et al. [2] categorized indicators for sustainable manufacturing and Park and Kremer [18] further categorized fifty-five environmental sustainability indicators using text mining-based objective information. However, Sikdar [19] claimed that no consensus exists on a reasonable taxonomy of sustainability-related metrics. Thus, indicators are defined inconsistently since every company, and indeed every opportunity for measured performance, has its own set of indicators.

2.2 Key performance indicator selection for sustainable manufacturing

Carlucci [20] noted that the selection of KPIs is necessary to assess the performance of a production management system. However, selecting a small set of KPIs from the large number of those available for a manufacturing process is often not straightforward. Secondly, selecting appropriate indicators to monitor the sustainability of processes and products is challenging due to the variety and complexity of those processes.

Efforts towards indicator selection include a methodology for establishing and improving performance measures that focus on overall equipment effectiveness [21]. Two related patents in the field exist. The first describes a method of selecting performance indicators so that they are relevant to an organization's business strategies [22]. The second describes KPI scorecard editor to rate different indicators against each other [23]. These patents, however, are proprietary and do not provide an open framework for KPI selection.

Garetti and Taisch noted the need for a structured framework to support selection of a suitable set of indictors [24]. To this end, a general KPI scheme for on-line process monitoring was developed in [25]. But, it does not provide a methodology to define new KPIs.

In summary, major problems for developing KPIs are (1) inconsistent definitions of KPIs, (2) a lack of an effective selection method for environmental KPIs for the manufacturing process, (3) a lack of KPI effectiveness evaluation methods, and (4) a lack of a KPI set composition method. This paper represents an initial step to addressing these problems. It proposes an approach that uses a common set of selection criteria rather than evaluating KPIs against each other.

2.3 Decision making under multiple criteria

Decision-making is the process of selecting a course of action from among alternative choices. The KPI selection methodology presented in this paper uses concepts of decision theory and multi criteria decision-making (MCDM), and is based on value-focused and value-function approaches. It includes both human judgment and quantitative methods.

Dieter and Schmidt [26] describe several steps for making choices to obtain the best outcome of a situation. The steps include establishing objectives, developing alternatives, evaluating alternatives against objectives, and choosing what holds the best promise for achieving the objectives. Evaluating alternatives is one of the most difficult steps because it requires overcoming, among others, making decisions under conflicting requirements, setting priorities, and establishing objectives

Each objective is a statement of what the decision maker wants to achieve in the decision context. The criteria represent objectives that KPIs should satisfy as they are evaluated. MCDM methods include the weighted sum method, weighted product method, and analytic hierarchy process, elimination and choice translating reality, and technique for order preference by similarity [27].

Another common approach is for stakeholders to rank alternatives from the best to the worst depending on their preference. Collins et al. proposed a selection and improvement methodology for KPIs based on the weighted sum of values determined by value functions [28, 29]. This paper further explores the use of value functions for selection criteria and use it for ranking candidate KPIs for selection of a final KPI set.

2.4 Value Functions for decision-making

Value-focused thinking is a way of using values to evaluate, rank, and choose the best among a set of alternatives [30]. Concepts of utility and value-focused thinking are more often used in economic analysis to understand preferences for products or investments. Value is a perceived benefit from acquiring and using a product or service, and upon which the motivation for making one choice over others is based. Values are obtained from value functions that are constructed by subject matter experts. But logical and systematic concepts are needed to qualitatively identify and structure the values that are appropriate to a situation while simultaneously constructing a value function [31]. Values are used to rank KPIs against the criteria.

Ezell [32] views the importance level assigned as a form of 'investment' on part of the stakeholder, and value as the benefit of doing so. Ranking candidate KPIs using value functions begins with identifying selection criteria followed by developing value functions for each criterion. Finally, a multiple objective decision making process using a value function for each criterion as proposed by Keeney [31] can be adopted to make criteria quantifiable. The process is described in the next section.

3 PROPOSED APPROACH FOR DEVELOPING KPI SETS

This section describes an approach to systematically rank candidate KPIs in order of effectiveness for sustainability assessment of a manufacturing process. It involves identifying candidate KPIs, selecting, ranking, and composing a final KPI set. These activities are illustrated in Figure 1. The first step is to establish organizational goals.

FIGURE 1 GOES HERE

3.1 Establishing KPI objectives

A KPI objective is a target of achievement to improve environmental sustainability of a manufacturing process. Individual KPI goals are obtained from organizational sustainability goals. KPI objectives represent activities to achieve identified KPI goals. Goals can be set as a normative standard for the organization or industry and should be applicable to all stakeholders.

3.2 KPI Identification

With sustainability goals established, the next step is to search literature and websites for candidate KPIs. KPI developers can first analyze KPIs currently in use and identify gaps in the KPIs necessary for the defined sustainability goals. If gaps exist and no KPIs can be found in literature, new KPIs should be defined. Candidate KPIs should be expressed using the format in ISO 22400-1 for ease of communication among stakeholders [10].

KPIs are often expressed in terms of associated metrics. Examples of metrics are energy consumption, water use, and material use. These metrics can either be measured directly (e.g. energy consumption measured with power meters) or estimated through physics-based equations (e.g. energy consumption estimated based on machine settings and material properties). Manufacturers should determine additional metrics not currently measured but necessary to address KPI objectives. When a new metric is needed, a manufacturer should consider the measurement methods (such as sensors or human input), the measurement costs, and the time needed to measure.

3.3 KPI Definition

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. For example, if the objective is to reduce energy waste at a process, then measuring both total energy and energy needed for a task (necessary energy) will be required. Example KPIs could be “total energy waste = total energy – necessary energy” or “energy waste efficiency = necessary energy/total energy.” The bottom-up approach is more useful when addressing the improvement of a single process.

The top-down approach focuses on defining a new KPI from the goals and identifying the necessary metrics to calculate that KPI. The method chosen is based on the manufacturer’s situation. The top-down approach is driven by organizational goals and may include several manufacturing processes relevant to the goal. Table 1 is an example of a KPI formatted using the ISO 22400-1 template [10].

TABLE 1 GOES HERE

3.4 KPI Selection

Once candidate KPIs are identified, experts and stakeholders are enlisted to rank the KPIs based on their effectiveness of sustainability assessment. The criteria for this ranking are determined independently from the KPIs themselves. The list of potential criteria can be extensive [33, 34, 35]. Therefore, a systematic approach involving multiple stakeholders is used to identify a set of selection criteria. Stakeholders include line managers, supervisors, and shop floor workers who make their proposals for selection criteria. This information is then aggregated. A final set of criteria is obtained after additional review by the stakeholders. Further, previous experience in similar situations can also be used to determine the number and type of criteria needed.

FIGURE 2 GOES HERE

Typically, criteria are not of equal weight during KPI selection. As such, experts develop a value function for each criterion, as mentioned in the previous section. Value functions capture experts' assessments of the value of a criterion. Developing a value function starts with the definition of importance levels to be assigned to the criterion. Figure 2 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 (horizontal) 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 (vertical) Y-axis. In this case, the experts give some value to a criterion that the work group can directly act on what is being measured by a KPI, i.e., whether a KPI is actionable. The experts in this example consider this information to have some value to enable other actions. But stakeholders would have to assign the maximum importance level for the most value that the work group can take action. Each importance level has a description that shows emphasis of the criterion during KPI ranking and a corresponding value or "benefit". Numerical values associated with both the importance level and the experts' evaluation of the criterions' value are represented on a graph. The shapes of value functions can differ depending on subject matter experts' expression of variation of importance of a given criterion with increasing assigned emphasis.

In the next step, stakeholders independently assign the levels of importance for all the criteria for each candidate KPI. 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.

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

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

3.5 KPI Composition

Different sustainability objectives often result in different KPIs as seen in Figure 3. To compose different KPIs, they must be on the same scale of measurement. Secondly, the KPIs should be assigned relative importance based on their perceived contribution to the sustainability goal. These two activities are referred to as normalization and weighting respectively. There are different methods used for normalization. Typically, the more important the KPI, the more weight it is assigned. Weights are dimensionless values.

KPI organization is a layered structure of KPI objectives, sub-goals, and sustainability goals. KPI objectives are at the bottom while sustainability goals are at the top. Sub-goals lie in between the sustainability goals and KPI objectives. The relationship between KPI objectives, sustainability sub-goals, and sustainability goals are expressed in the goal-objective structure. Using this structure, measurements based on KPIs can be properly aggregated to evaluate whether manufacturing processes meet the sustainability objective.

FIGURE 3 GOES HERE

4 DEMONSTRATION WITH A CASE STUDY

This section illustrates the procedure described above for selecting effective KPIs. We use a case of a powdered metal product manufacturing. The processes involved are compacting, sintering, and machining, as shown in Figure 4. This study focusses on the machining process.

FIGURE 4 GOES HERE

Three stakeholders (design manager, plant manager, and manufacturing engineer) are tasked to select appropriate KPIs that would assess the achievement of sustainability goals to make the following reductions within one year:

1) solid waste by 10 %
2) CO2 emissions by 20 %
3) energy consumption by 15 %

In the next step stakeholders search the literature for candidate KPIs that help achieve the above specified goals. Six candidate KPIs are identified. They are 1) material efficiency, 2) virgin material efficiency, 3) CO2 emissions, 4) N2O emissions, 5) energy per part, and 6) energy efficiency. These KPIs are deemed sufficient for the KPI goals and, therefore, no new KPIs are defined. The stakeholders next select the following criteria for ranking the KPIs:

1) Cost effectiveness: The degree of perceived cost benefit of implementing the KPI.

2) Quantifiable: The degree to which a KPI can be stated numerically and precisely.

3) Calculable: The degree of correctness and completeness of the calculation required to compute the value of the KPI.

4) Management support: The willingness of plant management to support the choice of appropriate KPIs, achievement of KPI targets, and performance of the tasks necessary to improve target KPI values.

5) Comparable: The degree to which historic data is maintained and available for comparison to current values.

6) Understandable: The degree to which the meaning of the KPI is comprehensible by team members, particularly with respect to corporate goals.

The value functions are then created by subject matter experts for each criterion. The stakeholders assign an importance level to the criterion for each KPI. For each importance level assigned, a value is obtained using the value functions. Table 2 shows the importance level on a scale 0-6 for each KPI assigned by one stakeholder. The values (obtained from the value function) vary in range 0-100. All three stakeholders perform the same process and their results averaged. The averages for all stakeholders per criterion, as well as the aggregated averages for all criteria (rating), are shown in Table 3.

TABLE 2 GOES HERE

TABLE 3 GOES HERE

The stakeholders scores show that the KPIs rank as follows: 1) Energy per Part, 2) Material Efficiency, 3) CO2 Emissions, 4) Virgin Material Efficiency, 5) Energy Efficiency, and 6) N2O Emissions. The stakeholders decide on a cutoff point of 475 and select Material Efficiency, Energy Intensity, and CO2 emissions to measure the sustainability objectives.

5 DISCUSSION AND CONCLUSION

Currently, standard procedures to select effective KPIs for manufacturing process sustainability do not exist. The paper has developed a method using selection criteria and value functions to rank candidate KPIs so that a final set is selected. The method combines both human input and quantitative analysis. The procedure will enable manufacturers to consistently select effective environmental KPIs across facilities to be shared among different manufacturers.

The approach is a step towards a standard guide for developing KPI sets for assessing environmental aspects of manufacturing processes. It complements existing standards for (1) KPI identification at operational level (ISO 22400-1), (2) for unit manufacturing process characterization (ASTM E3012-16), and (3) gate-to-gate environmental sustainability evaluation of manufacturing processes (ASTM E2986-15). This paper is a basis for a guide that has been proposed to the ASTM standard for members, consisting primarily of industrial practitioners, to review and comment.

However, membership is open to any interested party. A standard is expected to be completed soon.

The KPI selection process will better support researchers and practitioners in making informed use of KPIs if it is encoded into software. Procedures for selecting the stakeholders and subject matter experts can also be formalized and documented. Choices for criteria definition, value function development, final value aggregation methods as well as normalization and weighting methods can be made available.

This paper contributes to a wider field of using KPIs for performance measurement of manufacturing systems. Work on describing relationships between manufacturing KPIs has been initiated to enable understanding of which KPIs have the greatest impact on others as well as the type and form of impact. We anticipate that the results will include formal methods for developing and representing such relationships. The methods developed will be applied to environmental KPIs, which will further enhance the process of developing a final KPI set.

One of the major issues in KPI selection and application is that emphasizing one KPI may result in deterioration of another. By analyzing the interrelationships of various KPIs and their underlying metrics, it may be possible to calculate a similarity score, which could aid in the selection of the effective KPIs. For example, if multiple KPIs are based on the same metrics for computation, it might be possible to only use one KPI to measure towards the sustainability goal. On top of this, if one KPI that is already measured directly influences another KPI that is not measured, then it may be possible to calculate both KPIs without the need for additional data collection devices or measurements.

Repositories of KPIs for manufacturing processes will be helpful to provide pre-defined KPIs for selection of those suitable to the different specific processes being studied. Repositories should be easily accessible and extensible to organize KPIs as more are included. Advanced search capabilities should support accuracy and speed in finding appropriate KPIs and will be a topic of future research.

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DISCLAIMER

Certain commercial software products or services may be identified in this paper. These products or services were used only for demonstration purposes. This use does not imply approval or endorsement by NIST, nor does it imply that these products are necessarily the best for the purpose.

NOMENCLATURE

V	variables should appear in first column with the description in second column, m
I	all variables should appear in italics
tl	two-letter abbreviations should appear in italics
tla	three-letter abbreviations should not appear in italics
Re	Reynolds number and similar abbreviations do not use italics
T	use the “Tab” key to add more rows to this table

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Figure Captions List

Fig. 1 Illustration of the effective KPI identification and selection process

Fig. 2 Example of a value function for the criterion “actionable”

Fig. 3 KPI Composition for material efficiency

Fig. 4 Manufacturing process for powdered metal products – focus on machining

Table Caption List

Table 1 Example KPI – Total Energy Waste

Table 2 Design Manager Rankings

Table 3 Average stakeholder values and final aggregate

Figure 1: Illustration of the effective KPI identification and selection process

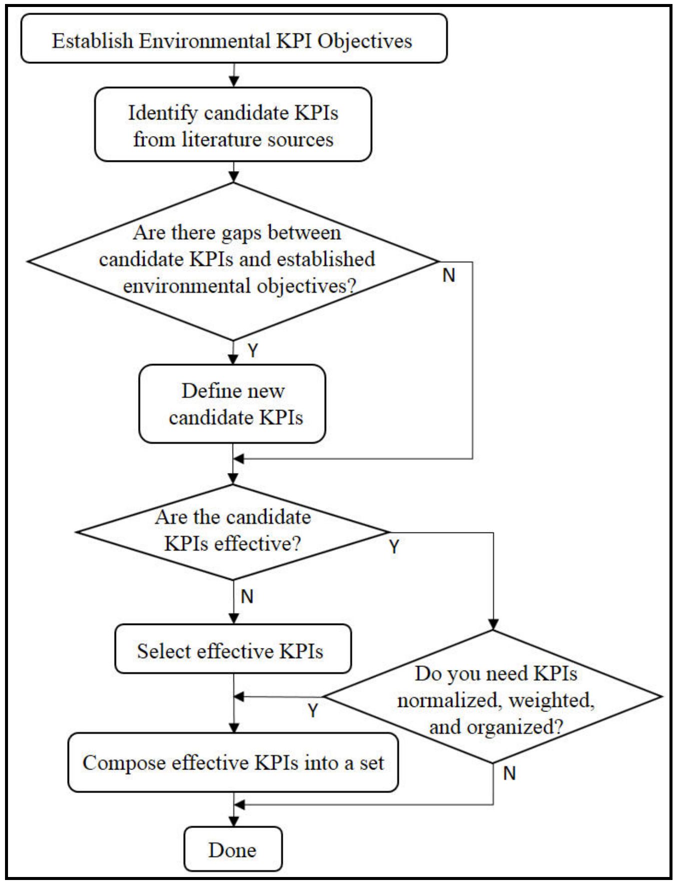

Figure 2: Example of a value function for the criterion "actionable"

Importance Level	Level	Experts' Value Assessment
Not important	0	0
Somewhat important	1	2
Fairly important	2	5
Important	3	12
Very important	4	35
Extremely important	5	100

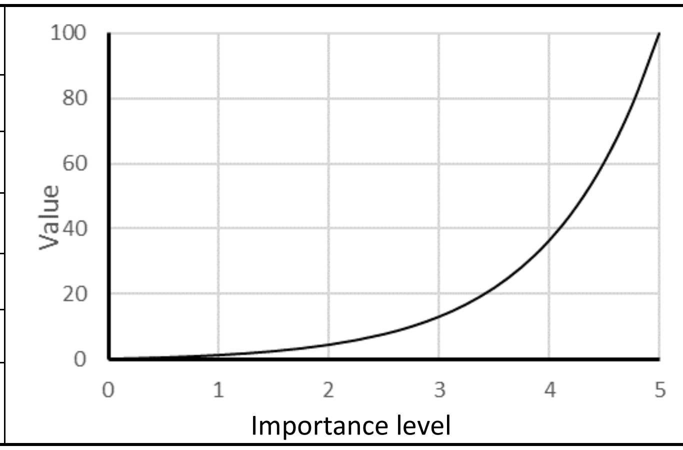

Figure 3: KPI Composition for material efficiency

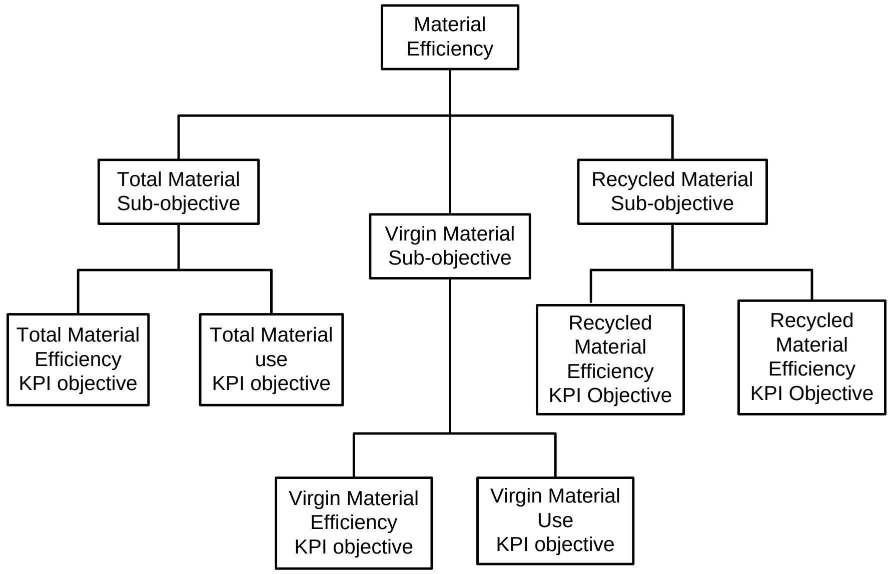

Figure 4: Manufacturing process for powdered metal products – focus on machining

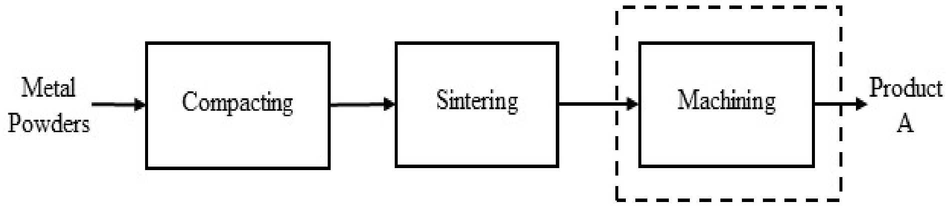

Table 1: Example KPI – Total Energy Waste

KPI description	
Content:	
Name	Total Energy Waste
ID	
Description	The total energy waste measures the difference between theoretical energy and the actual energy consumed by the process.
Scope	Process Level
Formula	Total Energy Waste = EC – NE, where EC = energy consumed by the process 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 energy waste at a process by comparing the energy needed at a process to the actual energy consumed.

Table 2: Design Manager Rankings

Stakeholder 1 (Design Manager)												
Legend: *L – Level* *V – Value*	Material Efficiency		Virgin Material Efficiency		CO_2 Emission		N_2O Emission		Energy per Part		Energy Efficiency	
	L	*V*	*L*	*V*	*L*	*V*	*L*	*V*	*L*	*V*	*L*	*V*
Cost Effectiveness	2	40	3	53	5	100	5	100	5	100	5	100
Quantifiable	6	100	6	100	5	36	5	36	6	100	6	100
Calculable	4	100	4	100	4	100	4	100	4	100	4	100
Management Support	5	100	4	72	4	72	4	72	3	47	3	47
Comparable	4	100	4	100	3	78	3	78	4	100	4	100
Understandable	5	100	5	100	5	100	5	100	5	100	5	100

Table 3: Average stakeholder values and final aggregate

	Material Efficiency	Virgin Material Efficiency	CO_2 Emission	N_2O Emission	Energy per Part	Energy Efficiency
Cost Effectiveness	49	49	100	64	90	64
Quantifiable	100	50	36	21	79	79
Calculable	93	93	100	93	100	85
Management Support	82	72	72	64	64	41
Comparable	85	85	85	61	84	76
Understandable	100	99	100	98	100	100
Aggregate value	**509**	448	**493**	402	**517**	444