Environmental KPI Selection Using Criteria Value and Demonstration

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ABSTRACT
Determining key performance indicators (KPI) is a first step in achieving environmental sustainability of manufacturing operations. KPI selection is a multi-criteria decision making problem, because of various criteria that must be considered. Intuitively, one can rank candidate KPIs by specifying a numerical value indicating the effectiveness of a KPI in satisfying each criterion. However, linking selection criteria to KPI objectives, ranking how well a KPI satisfying a given criterion, and assigning a value to each rank lead to better KPI rankings. Values for each score are crucial. This paper shows steps to capture values to derive a criterion value function that is used to rank candidate KPIs. Selected KPIs can be used for assessing and monitoring sustainability performance, which must be considered together with including traditional (e.g., throughput) measures. A machine shop is used to show how an objective of reducing emissions from energy use in manufacturing can be pursued by monitoring the energy used to produce a unit product.

Keywords: KPIs · Sustainability · Selection criteria · Value function

1 Introduction

Achieving sustainability of manufacturing processes requires efficient and effective methods for defining, selecting, deploying, and monitoring key performance indicators (KPIs). Selecting KPIs is a multi-criteria decision making problem for which several methods may be employed. One approach is to let each stakeholder assign a score of effectiveness of a KPI in satisfying a selection criterion. This process is repeated for each candidate KPI and final KPI ranks are obtained from resulting summation of these assigned scores.

Ezell (2007) and Collins et al. (2016) showed enhancement to this approach by capturing the internal "value" for each stakeholder for each score point on the Likert scale. Our previous research also used a multi-variate value model to provide stakeholders with the ability to score and evaluate candidate KPIs against each selection criterion (Kibira et al. 2017). The stakeholder assigns a score representing the degree of agreement (and quantification of this measure) to which a KPI satisfies a criterion. Each selection criterion is linked to the KPI objective. This way, each KPI is evaluated for its contribution to the defined environmental objective. The developed procedure has been contributed to an ASTM work item for a standard guide for identification and selection of environmental KPIs for manufacturing processes (ASTM International). Employing this procedure requires an in-depth understanding of developing and using value functions for selection criteria. This and the linking of criteria to KPI objective are discussed in this paper within the context of environmental sustainability assessment of manufacturing processes. This paper also discusses and demonstrates KPI deployment and performance monitoring in a machine shop.

Typically, criteria are used in KPI selection. As such, experts develop a value function for each criterion. Value functions capture experts' assessment of the value of a criterion. To develop a value function, Duarte et al. (2006) first defined the minimum and maximum possible measures of the score but assumed a linear relationship between assigned score and value. Keeney and Lilien's (1987) developed a method of assigning a value for each score for Very Large Scale Integrated (VLSI) circuit evaluation. Value functions were obtained by using subject matter expert allocated values at salient points on a common probability distribution or a linear function. This paper derives criteria value functions using a combination of above-mentioned approaches.

The rest of the paper is organized as follows. Section 2 presents concepts of the value model and shows steps to develop a value function. Section 3 presents a demonstration of implementing KPIs for performance assessment. Section 4 is a discussion and conclusion of the paper.

2 Criteria value based KPI ranking and deployment process

According to Keeney et al. (1993), values should be fundamental in any decision situation. Value-focused thinking leads to better structuring of objectives so that selected KPIs provide the best value for decision-making. Figure 1 shows the process of selecting and implementing KPIs for a manufacturing system, based on value functions.

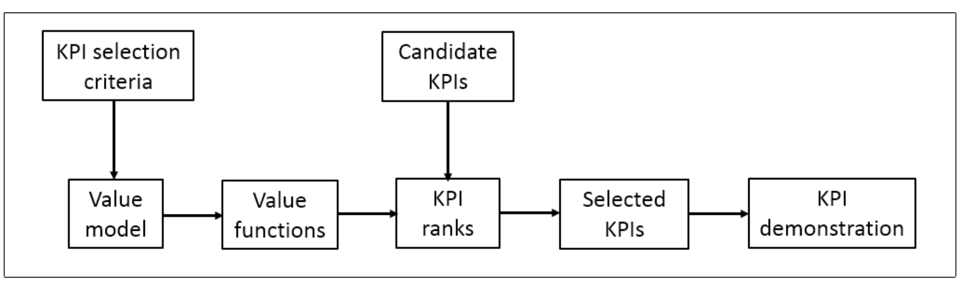

Figure 1: Process and steps of KPI selection and demonstration

Identifying KPI selection criteria: Selection criteria should be fundamental to the KPIs as opposed to being a means to another criterion (Keeney and Lilien1987). For example, a criterion such as "quantifiable" can be a means to ensure that a KPI is "calculable." Therefore, these two may not need to appear in the same criterion set. KPI objectives are used to identify criteria and are obtained from sustainability goal(s). For example, if reducing energy use by, say, 20% is the target, it implies that KPI should be measurable and/or computable. To obtain a complete representative list, criteria groups, e.g. financial-oriented or management-oriented criteria. To keep the analysis manageable, a decision can be made to select the best 5-10 criteria to make up the set.

Candidate KPIs: Typically, candidate KPIs are proposed by top management and presented to for evaluation. However, the candidate KPIs can also be identified if there is a gap between KPIs currently in use and those that are needed to achieve environmental objectives.

Value model for KPI ranking: For a value model, (1) each criterion is weighted for its contribution, and (2) each candidate KPI is measured against each measure criterion. Most previous researchers used the additive model to compute total value of a candidate KPI (Keeney and Lilien 1987; Keeney 1993; Ezell 2004; Duarte et al. 2006; Ezell 2007; Collins et al. 2016). Thus:

$$v(x_1, x_2, ..., x_n) = \sum_{i=1}^{n} w_i v_i(x_i) \quad \text{(i)}$$

Where v is the overall value function, and $v_i(x_i)$ are the individual criteria values at measurement level x_i, w_i are the scaling constants (weights), whose total should equal to 1.

$$\sum_{i=1}^{n} w_i = 1, \quad w_i > 0 \quad \text{(ii)}$$

Value function development

Horizontal measurement: This measurement scale is used to indicate the degree to which a KPI satisfies a criterion, as perceived by stakeholders. After identifying this scale, the minimum and maximum possible values are specified. For example, Table 1 shows measurement scales as well as minimum and maximum values for three of the criteria described in Kibira et al. (2017).

Table 1. Measurement scale of sample KPIs

Criterion	Designation	Measurement scale	Minimum	Maximum
Quantifiable	x_1	# of metrics and data	0	Total # of metrics and data
Cost effectiveness	x_2	$ (or max/min)	$0	$ max savings (or 1)
Calculable	x_3	# of variables and data	0	Total # of variables and data

Vertical measurement: Values for each level on the horizontal scale are determined by analysts and subject matter experts (or stakeholders). KPI values in general increase with degree of satisfaction of each criterion by the KPI. Therefore, value functions for KPI selection would in general exhibit an increasing trend. Alarcon et al. (2011) proposed four relationships (i.e., linear, convex, concave, and S-shaped) that a value function can take, as seen in Figure 2.

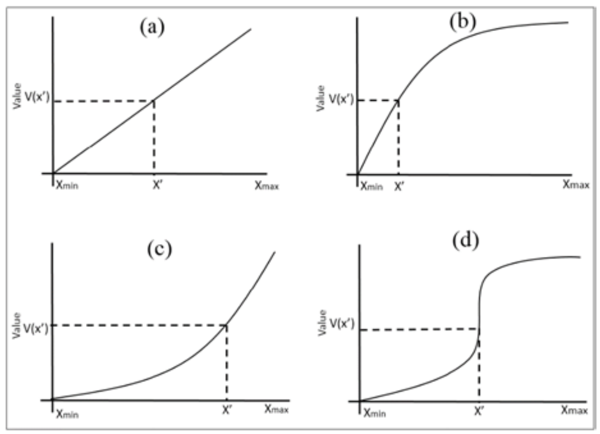

Figure 2: Common shapes of the value function.

To determine the actual values, let the minimum measurement be designated x_{min} and maximum be x_{max}. On a 0 – 1 scale for value, $v(x_{min}) = 0$ and $v(x_{max}) = 1$. Keeney and Lilien (1987) preferred to start with the mid-value (designated x'). The subject matter expert or stakeholders determines this value, where $v(x') = 0.5$. Other points between x_{min} and x' and between x' and x_{max} can be determined to yield additional points on the function v. If sufficient points can be garnered using experts, a sketch can complete the graph of the function.

KPI ranking: Next, for each KPI in the candidate set stakeholders independently assign a score showing agreement that the KPI satisfies the criterion. A value is obtained from the value function for each score. An average is calculated for the values obtained from all stakeholders for each criterion for each KPI.

3 Examples of applying steps in criteria value-based KPI selection

This section does not demonstrate a case study but presents examples to illustrate how the steps may be applied in a practical way. Some of the processes illustrated in Figure 1 are demonstrated in Kibira et al. (2017). Discussion will be on KPI selection criteria, value function development and KPI demonstration.

3.1 Selection criteria

Selection criteria are specified by production managers, supervisors, and shop floor workers. Lower-level KPI objectives for reducing material consumption include reduction in virgin material use and increase in use of recycled materials. The KPI objectives are used to identify criteria that would meet these objectives.

3.2 Value function for "Cost effectiveness" criterion

This criterion implies the degree of perceived cost benefit of implementing the KPI. Let the measure for this criterion be expressed as the "savings" measured on a scale from 0 to 10, which is the difference between the income (or saved costs) and expenditure of implementing a KPI. The satisfaction of the decision maker increases as the savings increase. Let the minimum savings, S_{min}, be 0 and the maximum, S_{max}, be 10.

The next step is to determine the shape of the value function. If savings through monitoring KPIs is a new strategic approach, any efforts in that direction are greatly encouraged. Therefore, initial measures are highly valued. A concave shaped value function, where the increase in value is maximized at the point of minimum measure, is suitable. See Figure 2(b). As you progress towards the maximum, the curve is more horizontal as the decision maker would generally assign less value to additions to high-level savings.

Once the general shape is established, what follows is to determine salient points on the curve. The expert is asked to express "How much savings, say *y*, such that the value from the minimum to *y* is equal to the value from *y* to the maximum?" Let this savings be labelled S' and x_1 designate the cost effectiveness criterion. On a scale from 0 – 1, $v_1(0) = 0$, $v_1(S') = 0.5$, and $v_1(S_{max}) = 1$. Proceeding from this point onwards, mid-value assessments are made for additional pairs of cost effectiveness (criterion) levels to generate other data points. Six candidate KPIs are identified.

3.3 Ranking KPIs

Stakeholders independently assigned a score on the measurement scale for each KPI against each criterion. The value corresponding to this score was obtained from the value function. The final value of a KPI was a sum of values obtained from all stakeholders for all the criteria. The values (obtained from the value function) are scaled to the 0-10 range. All three stakeholders perform the same process and their results averaged. The final ranking in an example used in (Kibira et al. 2017) is summarized in the chart in Figure 3. This chart shows that the "energy per part" KPI has the highest rank. This is used for monitoring energy performance in the demonstrated machine shop.

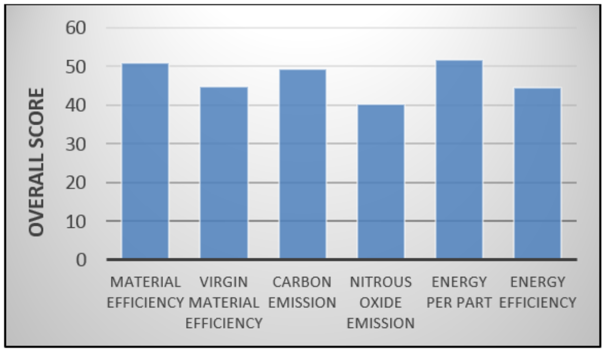

Figure 3: Final assessment of individual KPIs.

3.4 KPI demonstration

This section shows the monitoring of performance using the highest ranking KPI, i.e., energy per part. Let us assume that the high-level goal was "to reduce global warming potential due to energy consumption in the manufacturing process without compromising throughput." Such a goal is too broad for managers to evaluate the degree to which it is being achieved by the industry because different types of manufacturing equipment use different types of energy supplied from different sources. To evaluate achievement of the above goal, it is necessary to break down energy consumption into lower level objectives, which would be geared towards monitoring the use of each type of energy and its source.

To demonstrate achieving lower level objectives, a case study of a small machine shop that manufactures metal products is used. The shop comprises of a foundry, one milling machine, one lathe machine, and an ultrasonic inspection center. There are two classes of products: A and B. Figure 4 shows the work flow. Production starts when the parts are loaded onto the shop. After casting, products A requires turning operations while products B require milling. Both products are completed by drilling holes into them. Some turned products do not need drilling. After processing, all parts pass through the inspection station.

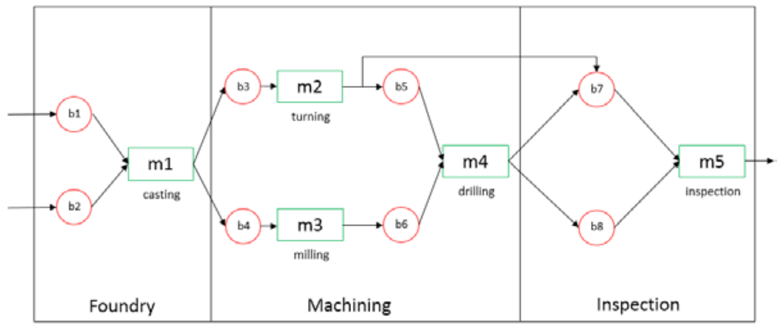

Figure 4: Workflow through the shop.

Energy modeling and simulation: A discrete event simulation model of the shop was constructed using AnyLogic simulation software tool to generate energy use data. To attribute energy to a unit part, we use a framework like one developed by Seow et al. (2011). Two types of energy are distinguished: direct and indirect. Direct energy is the type used in the actual production process, e.g., heat to melt metal. Indirect energy is that used in the ambient working area such as heating, ventilation, and air-conditioning (HVAC), and lighting.

Direct energy: The direct energy for the casting process is obtained by combining energy used to bring the metal from room temperature to melting temperature as well as the fusion energy required. Machining energy is related to machining time. Both these quantities are calculated using empirical expressions for machining of mild steel products (Sonmez et al. 1999; Sardinas et al. 2006). For product inspection, the energy consumed during is equal to the energy rating of the ultrasonic tester multiplied by duration of the inspection.

Indirect energy: Indirect energy consumed in each section of the shop depends on the type of manufacturing activity. Indirect energy is calculated by considering HVAC and lighting rating requirements for the nature of manufacturing activities carried out in these sections. Energy per part is obtained by dividing the result by the total of parts produced.

3.5 Simulation output

This section describes a case study of tracking energy consumption using an energy KPI. This KPI is selected based on the analysis of value functions on relevant criteria. Experiments were carried out to investigate the impact of batch size on both energy consumptions per part and the total number of units produced. Batch size is the variable used because it effects many factors including setup time and setup cost, inventory levels, lead times, safety stock, and order fulfilment. In general, small batch sizes are associated with higher overall set-up time while large batch size, without lot-splitting, can lead to increased idling and thus, reduced throughput. The effect of batch size is investigated through a simulation experiment to determine a balance between energy consumption and overall throughput in the multi-stage production environment. Note that set-up time for casting is not constant for all batch sizes.

The energy consumption quantities are shown in the graph in Figure 5. For each experiment, Parts A and B are loaded alternately onto the shop in batches of equal size. Batches are varied from an initial size of 5 units. For a batch size less than ten units, there is significant increase in energy use per part while any batch sizes exceeding 20 units, the decrease in energy use is not significant. On the other hand, the total number of units produced falls almost evenly with increase in batch size. The decision maker can use this graph to balance energy per part and throughput for each situation.

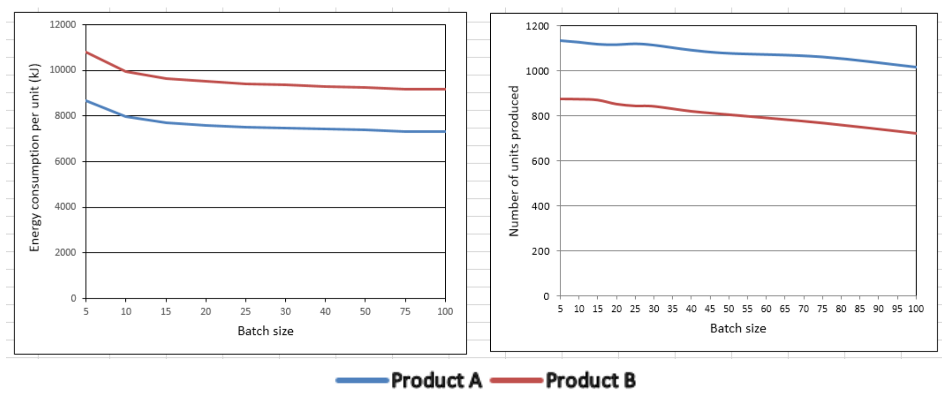

Figure 5: Variation of energy consumed per part with batch size

4 Summary and discussion

This paper has discussed using value of a score for a KPI against a criterion to evaluate a candidate KPIs. This approach was adopted after realizing that the relationship between such scores and benefit from the score is not always linear. The benefit and hence, value of a KPI could increase rapidly from the minimum level against a given criterion as efforts are made to its introduction. Alternatively, the value could be judged as insignificant until a level of agreement or satisfaction that a KPI meets the criteria exceeds a given point on the measurement scale. This concept of value, as a basis for decision-making is relevant to the KPI selection process and largely hinges on constructing value functions for each criterion.

The value functions described in this paper has been included in a draft standard guide for identification and selection of environmental KPIs for manufacturing processes. Specifically, our work results in an appendix in the draft standard. The value functions used in selecting KPIs is necessary so that selected KPIs are effective to stakeholders.

Expert knowledge and stakeholder contribution is crucial for deriving value functions used for ranking candidate KPIs. Selection for KPIs is based on the resulting ranks. Selected KPIs can be used for assessing and monitoring system performance including traditional (e.g., throughput) and sustainability (e.g., energy consumption) measures. Analysis and tradeoff can be made between these measures while determining a production plan by, for example, understanding how they impact a common factor such as net income. During system design, simulation model of a system can be employed. Furthering this work, the analyst can use simulation to investigate data processing and aggregation methods for decision levels at different control levels as well as possible interactions between different KPIs.

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