S-PI: A performance measurement system using an S-curve

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**ABSTRACT**

This method is a tool for evaluating the performance of any production system. It is based on the work of (1), with an evaluation structure consisting of a three-level hierarchy. Evaluation groups are at the top level, below which groups of metrics or key performance indicators (KPIs) are located; performance indicators (PIs) are located below the KPIs. To consolidate several types of metrics, in a single evaluation, it is necessary to normalize the values. This study overcomes the deficiencies of the original method, which linearly normalizes the PIs between 0 and 1. For an indicator with a goal of 100%, a compliance of 70% would be evaluated as 70% of the desired value. In reality, the decision maker may consider 70% to be equivalent to 30% of the desired value. To more realistically simulate the evaluator’s preference scale, an S-shaped curve based on the Weibull distribution is adopted. This curve must be calibrated to reflect the preferences of the evaluator. This study shows all the steps of structuring an evaluation system, with details for the calibration of the S-curve parameters.

- Evaluation scales are not linear.
- The S-curve better reflects stakeholder preferences.

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Specifications table

| Subject Area:  | Engineering                          |
|---------------|--------------------------------------|
| More specific subject area: | Industrial Engineering                |
| Method name:  | S-PI Performance Measurement System |
| Name and reference of original method: | Performance Measurement System. |
|               | Lohman, C., Fortuin, L., Wouters, M., 2004. Designing a performance measurement system: A case study. European Journal of Operational Research 156, 267–286. |

Introduction

Every organization faces the problem of evaluating the performance of its production system in its various aspects. A method established in recent years was proposed by [1] based on the balanced score card [2]. Other authors have addressed the challenge of building evaluation systems that monitor production systems and serve as a control and guidance instrument for better performance. The system must include all relevant aspects, must be measurable, and must be consistent with the objectives of the organization. The topic continues to arouse great interest in industry and academia. Since 1992, 110,226 articles have been published with the keyword “performance measurement system”. There were 767 articles in 1992, reaching 9498 articles in 2019 [3]. More recently, studies have been applied in various areas such as industry 4.0 [4,5,6], the environment [7,8,9,10] and aviation [11]. Studies continue to be produced in traditional areas such as supply chain management [12,13], the hotel industry [14], and civil construction [15,16].

This work details the main method presented in the original article KRAKOVICS, F., Leal, JE, Mendes, P. Jr., Santos, LR Defining and calibrating performance indicators of a 4PL in the chemical industry in Brazil. International Journal of Production Economics. 115, 2008, Vol. 2, pp. 502–514.

The structure of the performance system

This work assumes that the reader has basic knowledge about evaluation methods. Interested parties can consult the work of [17] for a better view of the basic concepts that guide the construction of a performance evaluation system. The hierarchical structure for the construction of the system can be seen in Fig. 1.

Hierarchy of indicators

The organization defines areas, or evaluation groups, within which it structures its hierarchy. This structure should be aligned with and reflect the objectives of the organization. At the second level, below each group, evaluation subgroups or KPIs are defined. Below each subgroup, performance indicators (PIs), which are calculated from the performance measurements (PMs), are defined. The indicators represent measurements of attributes or activities of different natures with different performance metrics. We differentiate the PMs, which measure the direct performance of the organization unit in a certain activity, and the PIs, which are the transformations of the measurements into comparable metrics for different activities. Therefore, for consolidation and comparison in the system, a normalization of the measurements for the PI values, in general, to a scale between 0 and 1 is first required.

Fig. 1. Hierarchy of metrics (adapted from [1]).
Table 1
Calculation of weights.

| Row | Alternative | b = 1 | 2   | 3   | 4   | Sum  |
|-----|-------------|-------|-----|-----|-----|------|
| 2   | b_j         | 1     | 3   | 9   | 7   |      |
| 3   | 1/b_j       | 1     | 0.333 | 0.111 | 0.1428 | 1.5873 |

Weight of each element in the hierarchy

Each group in the hierarchy receives a weight indicating its importance to the immediate higher level. Thus, with the PIs and their weights in relation to the KPIs and with the KPIs and their weights in relation to the groups, the contribution of each PI to the evaluation of the cluster performance can be calculated, and the cluster performance can be determined.

Bases of calculation

Calculating the performance of each cluster

Each cluster $i$ ($i = 1, \ldots, NC$) has $NK_i$ KPIs at the second level of the system ($KPI_{ij} = 1, \ldots, NK_i$). Each $KPI_{ij}$ has $NI_{ij}$ PIs at the third level of the system ($PI_{ijl}, l = 1, \ldots, NI_{ij}$). Each $KPI_{ij}$ is associated with a weight $WK_{ij}$ representing the relative importance of the KPI of cluster $i$. Each $PI_{ijl}$ is associated with a weight $WI_{ijl}$ representing the relative importance of the PI to the corresponding KPI. The cluster value performance may be calculated as:

$$C_i = \sum_{j=1}^{NK_i} WK_{i,j} \cdot KPI_{i,j} = \sum_{j=1}^{NK_i} WK_{i,j} \cdot \left( \sum_{l=1}^{NI_{ij}} WI_{i,j,l} \cdot PI_{i,j,l} \right)$$  \hspace{1cm} (1)

If the evaluator wants a global evaluation for the organization, he or she can also define weights $W_i$ for each of the NC clusters in relation to the global evaluation and arrive at the global performance $G$:

$$G = \sum_{i=1}^{NC} W_i \cdot C_i$$  \hspace{1cm} (2)

The contribution of each $PI_{ijl}$ of $KPI_{ij}$ to the performance of cluster $i$ can be calculated with Eq. (3)

$$C_{il} = WK_{i,j} \cdot WI_{i,j,l} \cdot PI_{i,j,l}$$  \hspace{1cm} (3)

Defining the weights at each level

To obtain the weight $w_i$ of each element $j$ of a level in front of the element in the upper level, the AHP-express method can be used [18]. Given the alternatives for comparison against a given criterion (in this case the element of the higher level), the evaluator must first choose the base alternative that seems most important. This base alternative receives a value of 1, and the others a value between 2 and 9, according to [19], which expresses the dominance of the base alternative over each of the others. Eq. (4) is used:

$$w_j = \frac{1}{b_j} \cdot \frac{1}{\sum_{k=1}^{na} \frac{1}{b_k}}$$  \hspace{1cm} (4)

where $w_{ij}$: weight assigned to the alternative, or element $j$; na: number of alternatives; $b_j$: measure of dominance of the base alternative over alternative $j$.

The Table 1 is an example of a calculation using an Excel spreadsheet. Alternative 1 is chosen as the basis. In the second row, the alternatives are compared with the base alternative. The third
row contains the calculated inverse of the values of line 2. The Sum column contains the sum of the inverses. This sum is inverted, and the resulting value is fixed as absolute with the shortcut “F4”. Multiplying this value with each element in row 3 gives the weight $w_j$ of each alternative in row 4.

**Normalization using the S-curve**

Normalization transforms direct measurements of attributes or activities into indicators that reflect the usefulness of the measurement for the decision maker. The evaluator should define his or her preference scale using a scale from 0 to 1. The S-curve is the form of a Weibull distribution function used to express this utility.

$$F_x(x) = 1 - e^{-\left(\frac{x}{\bar{x}}\right)^\gamma}$$  \hspace{1cm} (5)

This function ranges from 0 to 1, representing values with a minimum of 0 and increasing to 1. It therefore represents increasing functions in $x$ and is used to represent the usefulness of the measurements, where the better the measurement evaluated, the higher its value. Examples include delivery punctuality and delivery accuracy. Other measurements are more useful the lower their value. This is the case for delivery delays and shipping errors. In this case, the S-curve is:

$$F_x(x) = e^{-\left(\frac{x}{\bar{x}}\right)^\gamma}$$  \hspace{1cm} (6)

where $x$ is the measurement value of the activity or attribute. For increasing utility with the measurement value, the normalized value $PI$ is:

$$PI(x) = 1 - e^{-\left(\frac{x}{\bar{x}}\right)^\gamma}$$  \hspace{1cm} (7)

For decreasing utility with the measurement value, the normalized PI value is:

$$PI(x) = e^{-\left(\frac{x}{\bar{x}}\right)^\gamma}$$  \hspace{1cm} (8)

In both cases, it is necessary to find the parameters $\theta$ (theta) and $\gamma$ (gamma) for each function. These parameters can be calibrated by defining only two performance values and their corresponding normalized PI values. A bad value of performance measurement (BPM) is associated with the bad performance index (BPI) value of 0.1, and an acceptable performance measurement (APM) is associated with the acceptable performance measurement API value of 0.6 or 0.7 according to the evaluator’s criteria. The BPM and APM values already indicate whether the utility function is increasing or decreasing. If $APM > BPM$, the function is increasing; otherwise, the function is decreasing.

In the case of increasing utility functions, the value of the gamma parameter, $\gamma$, is calculated with Eq. (9):

$$\gamma = \frac{\ln(\ln(1 - BPI))/(\ln (1 - API))}{\ln\left(\frac{BPM}{APM}\right)}$$  \hspace{1cm} (9)

And the theta parameter, $\theta$, is calculated with:

$$\theta = \frac{API}{(-\ln(1 - APM))^{1/\gamma}}$$  \hspace{1cm} (10)

In the case of decreasing utility functions, the parameters are respectively calculated with:

$$\gamma = \frac{\ln(\ln(BPI))/(\ln (API))}{\ln\left(\frac{BPM}{APM}\right)}$$  \hspace{1cm} (11)

$$\theta = \frac{API}{(-\ln(API))^{1/\gamma}}$$  \hspace{1cm} (12)
Table 2
Hierarchical structure of performance evaluation of a liquid bulk terminal.

| Criteria                        | Key Performance Indicators                                      | Regular performance indicators                                      |
|---------------------------------|-----------------------------------------------------------------|---------------------------------------------------------------------|
| Response to Clients             | Flexibility                                                     | Types of modes for receiving/shipping                                |
|                                 |                                                                  | Scheduling - offshore                                                |
|                                 |                                                                  | Scheduling - onshore                                                 |
|                                 | Aggregated Services                                             | Blending of products with additives                                 |
|                                 |                                                                  | Formulation                                                         |
|                                 |                                                                  | Blending for classification                                          |
|                                 |                                                                  | Laboratory analyzes                                                 |
| Financial Aspects and Resources | Financial Factors                                               | Total logistics costs                                                |
|                                 |                                                                  | Price of the service                                                |
|                                 | Resources                                                       | Cost of failures                                                    |
|                                 | Use of Assets                                                   | Technology for scheduling/optimization                               |
|                                 |                                                                  | Degree of automation in the process/Control                         |
| Environment and Safety          | Atmospheric emissions                                           | Turnover of fixed assets                                            |
|                                 | Leaks/spills                                                    | Total volumetric capacity                                           |
|                                 | Accident frequency rate                                         | Location and accesses                                               |
| Internal Processes              | Service Quality                                                 | Compliance with logistical planning                                 |
|                                 |                                                                  | Product losses                                                      |
|                                 | Productivity                                                    | Layover time - offshore mode                                         |
|                                 |                                                                  | Availability of storage facilities                                  |
|                                 |                                                                  | Availability of receiving/shipping facilities                       |
|                                 |                                                                  | Layover time - onshore mode                                          |

Source. [20].

The calibration of the S-curve parameters follows the steps:

- Define the values of BPM and BPI and APM and API.
- Compute $\gamma$ with Eq. (9) for ascending values or Eq. (11) for descending values.
- Compute $\theta$ with Eq. (10) for ascending values or Eq. (12) for descending values.
- With $\theta$ and $\gamma$, use Eq. (7) for ascending values or Eq. (8) for descending values to determine the value of a performance indicator PI given a performance measurement $x$.

Steps of the complete procedure:

I. Define the indicator hierarchy structure.
II. Define the weights of each element in the hierarchy.
III. Define the metrics for the performance measurements of each activity associated with the performance indicator.
IV. Calculate the normalized values of each performance indicator.
V. Calculate the performance values of each group or the entire evaluation system.

Example of the performance evaluation of a liquid bulk terminal

Vieira and Leal (2020) present a hierarchical structure for liquid bulk terminal evaluation, summarized in Table 2.

Let us take, for example, the group of internal process indicators. This group has two KPIs: service quality and productivity, each with its own PIs. The structure of this part of the hierarchy is represented in Fig. 2:

The performance indicators are shown in Table 3 for each PI.

Defining weights in the hierarchy.

Using AHP-express Eq. (4) and defining an alternative (b) as the best, the weights of the KPIs against the cluster can be obtained in Table 5.
Internal Processes

Service Quality

Product losses

Productivity

Compliance with logistical planning

Loading/Unloading time

Availability of receiving/shipping facilities

Availability of storage facilities

Layover time – onshore mode

Layover time – offshore mode

Fig. 2. Partial hierarchy of indicators for a bulk liquid terminal.

Table 3
KPIs and PIs for example criteria.

| Criteria               | Key Performance Indicators   | Regular Performance Indicators                                                                 |
|------------------------|------------------------------|------------------------------------------------------------------------------------------------|
| Internal Processes     | Flexibility                  | Compliance with logistical planning                                                               |
|                        |                              | Product losses                                                                                   |
|                        |                              | Loading/Unloading time                                                                            |
|                        |                              | Availability of receiving/shipping facilities                                                     |
|                        |                              | Availability of storage facilities                                                               |
|                        | Productivity                 | Layover time – onshore mode                                                                      |
|                        |                              | Layover time – offshore mode                                                                     |

Table 4
Formula and units of measure for each PI of the example.

| Regular Performance Indicators                       | Formula                                                                 | Unity                 |
|------------------------------------------------------|------------------------------------------------------------------------|-----------------------|
| Compliance with logistical planning                  | $m^3$ fulfilled/$m^3$ scheduled                                        | %                     |
| Product losses                                       | $m^3$ dispatched/$m^3$ received                                        | %                     |
| Loading/Unloading time                               | Loading (unloading) time/average time in the local market             | dimensionless         |
| Availability of receiving/shipping facilities        | available capacity/installed capacity                                 | %                     |
| Availability of storage facilities                   | $m^3$ available/$m^3$ installed                                       | %                     |
| Layover time – offshore mode                         | Average overlay/average local market overlay                          | dimensionless         |
| Layover time – onshore mode                          | Average overlay/average local market overlay                          | dimensionless         |

The same procedure is performed to estimate the weights of each PI against the respective KPI in Tables 6 and 7.

For each PI, two pairs of values are defined by the evaluator: a BPM with a BPI and an APM with an APL. Fig. 3 presents the values of the gamma and theta parameters using Eqs. (9) and (10) for ascending utility curves and Eqs. (11) and (12) for descending utility curves. The figure also gives the PI values for actual measures of the indicators using Eq. (7) for ascending curves and Eq. (8) for descending curves.

For the spreadsheet structure and the values shown in Fig. 3 the gamma calculation of row 2 is obtained with the formula:

$$= \text{IF} \left( \text{D2} > \text{B2}; \ln \left( \frac{\ln (1-C2)}{\ln (1-E2)} \right) \left/ \ln \left( \frac{\text{B2}}{\text{D2}} \right) \right; \ln \left( \frac{\ln (C2)}{\ln (E2)} \right) \left/ \ln \left( \frac{\text{B2}}{\text{D2}} \right) \right) \right)$$.
Table 5
KPI weights against the internal processes cluster.

| bj | 1   | 3   | Sum  |
|----|-----|-----|------|
| 1/bj | 1.000 | 0.333 | 1.333 |
| wj | 0.750 | 0.250 | 1.000 |

Table 6
Weights for the Pls of the KPI service quality.

| Compliance with logistical planning | b = Product losses | Sum  |
|------------------------------------|-------------------|------|
| bj | 5  | 1   | 1.200 |
| 1/bj | 0.200 | 1.000 | 1.200 |
| wj | 0.167 | 0.833 | 1.000 |

Table 7
Weights for the Pls of the KPI productivity.

| Indicator                                      | BP  | BPI | AP  | API | alfa | teta | PM  | PI  | PMGoal | Pgoal |
|------------------------------------------------|-----|-----|-----|-----|------|------|-----|-----|--------|-------|
| Compliance with logistical planning            | 90  | 0.1 | 95  | 0.6 | 40.005 | 95.208 | 98  | 0.958 | 99     | 0.992 |
| Product losses                                  | 1.0 | 0.1 | 5   | 0.6 | 2.172  | 8.812  | 3   | 0.845 | 2      | 0.933 |
| Loading/Unloading time                          | 1.2 | 0.1 | 1   | 0.6 | 8.259  | 1.085  | 0.95| 0.716 | 0.93   | 0.755 |
| Availability of storage facilities             | 85  | 0.1 | 95  | 0.6 | 19.446 | 95.428 | 95  | 0.600 | 98     | 0.813 |
| Availability of receiving/shipping facilities  | 90  | 0.1 | 96  | 0.6 | 33.534 | 96.951 | 93  | 0.271 | 98     | 0.898 |
| Layover time – offshore mode                   | 1.2 | 0.1 | 0.98 | 0.6 | 7.435  | 1.073  | 1   | 0.552 | 0.95   | 0.667 |
| Layover time – onshore mode                    | 1.1 | 0.1 | 0.95 | 0.6 | 10.271 | 1.014  | 0.9 | 0.746 | 0.9    | 0.746 |

Fig. 3. Parameter estimation and PI calculation.

The theta values of row 2 are obtained with the formula:
= IF (D2> B2; D2/((- LN (1-E2)) ^ (1/F2)); D2/((- LN (E2)) ^ (1/F2))).

The spreadsheet also calculates the PI values for the current PMs and the Plgoal values for target measurements of each indicator (PMgoal). In the spreadsheet, the PI values of row 2 are calculated with:
= IF (D2> B2; 1-EXP (- ((H2/G2) ^ F2)); EXP (- ((H2/G2) ^ F2))).

The PI target values are calculated with the formula:
= IF (D2> B2; 1-EXP (- ((J2/G2) ^ F2)); EXP (- ((J2/G2) ^ F2))).

Note that the logical comparison IF (D2> B2...) detects an ascending or descending curve so that the corresponding formulas can be applied.

Using the weights of the Pls related to the KPIs and the weights of the KPIs related to the clusters, the overall performance measures for the clusters are calculated and are presented in Table 8.

The same weights are now used to calculate the goal performance for the clusters in Table 9.

The columns “Pl to Cluster” in both tables give the contribution of the performance of each PI to the cluster performance. Influenced by the weights given by the evaluator, these “Pl to Cluster” values may be used to correct the performance of each activity in the cluster. The comparison of the current and the goal “Pl to Cluster” values may also help suggest actions to improve the service toward the goal values.
Table 8
Actual performance.

|                                | PI   | PI weight | KPI weight | PI to Cluster | KPI to Cluster | Cluster |
|--------------------------------|------|----------|------------|---------------|----------------|---------|
| Compliance with logistical planning | 0.958 | 0.167    | 0.750      | 0.120         | 0.864          | 0.761   |
| Product losses                  | 0.845 | 0.833    | 0.750      | 0.528         | 0.018          | 0.450   |
| Loading/Unloading time           | 0.716 | 0.100    | 0.250      |               | 0.023          | 0.071   |
| Availability of storage facilities | 0.600 | 0.166    | 0.250      | 0.025         | 0.013          |         |
| Availability of receiving/shipping facilities | 0.271 | 0.498    | 0.250      | 0.034         |               |         |
| Layover time - offshore mode     | 0.552 | 0.166    | 0.250      | 0.023         |               |         |
| Layover time - onshore mode      | 0.746 | 0.071    | 0.250      | 0.013         |               |         |

Table 9
Goal performance.

|                                | PI   | PI weight | KPI weight | PI to Cluster | KPI to Cluster | Cluster |
|--------------------------------|------|----------|------------|---------------|----------------|---------|
| Compliance with logistical planning | 0.992 | 0.167    | 0.750      | 0.124         | 0.942          | 0.905   |
| Product losses                  | 0.933 | 0.833    | 0.750      | 0.583         | 0.019          | 0.791   |
| Loading/Unloading time           | 0.755 | 0.100    | 0.250      |               | 0.010          |         |
| Availability of storage facilities | 0.813 | 0.166    | 0.230      | 0.034         | 0.005          |         |
| Availability of receiving/shipping facilities | 0.839 | 0.498    | 0.230      | 0.104         |               |         |
| Layover time - offshore mode     | 0.667 | 0.166    | 0.250      | 0.028         |               |         |
| Layover time - onshore mode      | 0.746 | 0.071    | 0.250      | 0.013         |               |         |

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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