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Integral indicator of ecological impact of the Croatian thermal power plants[☆]

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ABSTRACT

The main goal of this paper is to present the methodology of construction of the Integral Indicator for the Croatian Thermal Power Plants and the Combined Heat and Power Plants. The Integral Indicator is intended to compare the Power Plants according to a certain criterion. The criterion of the ecological impact is chosen. The following features of the power plants are used: generated electricity and heat; consumed coal and liquid fuel; sulphur content in fuel; emitted CO_2, SO_2, NO_x, and particles. The linear model is used to construct the Integral Indicator. The model parameters are defined by the Principal Component Analysis. The constructed Integral Indicator is compared with several others, such as Pareto-optimal slicing indicator and Metric indicator. The Integral Indicator keeps as much information about the waste measures of the power plants as possible; it is simple and robust.

1. Introduction

"The Directive concerning integrated pollution prevention and control and applying to all industrial plants, including HEP's (Hrvatska Elektroprivreda [1],) large combustion plants, lays down measures designed to reduce emissions to air, water and soil and the generation of waste, measures to improve energy efficiency and water use, and measures to prevent accidents that have adverse impact on the environment, applying best available techniques. HEP commenced preparatory activities for the alignment with national policy measures to mitigate climate change, such as the introduction of a carbon dioxide fee (CO_2) and preparations for joining the EU Greenhouse Gas Emission Trading Scheme" [2].

Nowadays the problem of waste reduction, connected with electricity generation using fossil fuels, is very important [3–8]. We investigate the problem of the waste measurement and discuss several techniques for the integral indicator construction. The application area of these indicators is the ecological impact of the Croatian Thermal Power Plants and Combined Heat and Power Plants [9].

An integral indicator is a measure of the object's quality: "fitness for use" [10], defined according to specific goals. We consider an integral indicator as a scalar, corresponding to an object [11]. It is a combination of features (waste measurements) that describe an object from the set of comparable objects (power plans) [12,13]. Features are individual measurable properties of the objects, being observed or compared. "An environmental indicator is a numerical value that helps to provide insight into the state of the environment or human health. Indicators are developed based on quantitative measurements or statistics of environmental condition that are tracked over time. Environmental indicators can be developed and used at a wide variety of geographic scales, from local to regional to national levels" [14].

To construct an integral indicator several steps must be performed. First, a quality criterion (or a criterion of comparison) must be chosen [15,16]. The integral indicator must express this criterion. The collected objects, here the Croatian Thermal Power Plants, must be comparable in terms of their impact on the environment [17]. Second, a set of features must be selected according to this criterion. An optimal value must be assigned to each feature [18]. Here the principle "the greater the better" is followed: the greater value of any feature causes the greater, "the better", value of the integral indicator. The features must be measured in linear or binary scales. The nominal and the ordinal-scaled features must be transformed to the binary ones [19]. Third, a data table "objects-features" must be fulfilled, see Table 1 below. Optionally, the expert estimations of the integral indicator must be collected. Further, we suppose that the data table contains no outliers and missed values. Also we suppose that multicollinearity of the feature set is not significant [20,21]. In this paper we define the integral indicator as the linear combination of the features.

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Table 1
The data used for the integral indicator construction.

N	Power Plant	Available net capacity (MW)	Electricity (GWh)	Heat (TJ)	SO_2 (t)	NO_x (t)	Particles (t)	CO_2 (kt)	Coal (t)	Sulphur content in coal (%)	Liquid fuel (t)	Sulphur content in liquid fuel (%)	Natural gas (10^3 m^3)
1	Plomin 1 TPP	98	452	0	1950	1378	140	454	198,454	0.54	431	0.2	0
2	Plomin 2 TPP	192	1576	0	581	1434	60	1458	637,924	0.54	367	0.2	0
3	Rijeka TPP	303	825	0	6392	1240	171	616	0	0	199,735	2.2	0
4	Sisak TPP	396	741	0	3592	1049	255	573	0	0	111,591	1.79	121,459
5	TE-TO Zagreb CHP	337	1374	481	2829	705	25	825	0	0	80,423	1.825	308,502
6	EL-TO Zagreb CHP	90	333	332	1259	900	19	355	0	0	38,982	2.1	125,879
7	TE-TO Osijek CHP	42	114	115	1062	320	35	160	0	0	36,668	1.1	24,337
	Optimal value	max	max	max	min	min	min	min	min	min	min	min	min

The paper [18] reads: "The discriminatory ability of the indicator should be evaluated against program data quality objectives and constraints. It should be demonstrated how sample size, monitoring duration, and other variables affect the precision and confidence levels of reported results, and how these variables may be optimized to attain stated program goals."

There are two approaches to construct the integral indicator. The first one is called "non-supervised" [22]. According to this approach, the integral indicator is defined by a selected model: a function of the measured features. Only the data table "objects-features" is required. The second one is called "supervised" [23]. According to this approach, to construct the integral indicator, one needs the data table, the selected model, the expert estimations of the desired integral indicator and, if it is possible, the expert estimations of the features' importance. The expert estimations of the object quality (ecological impact) also could be used as separate features in the data table or could be represented as a joined concordant set [24,25] and considered as an integral indicator itself. There are lots of algorithms to construct the integral indicator [11]. However, when the model is chosen and the integral indicator is calculated, the following question arises: how to show adequacy of it? To answer this question analysts invite experts [25]. The experts express their opinion and then the second question arises: how to show that expert estimations are valid? Below the system of supervised and non-supervised algorithms is presented to show adequacy of the constructed integral indicators.

The proposed algorithms and the Integral Indicator were suggested for application in Hrvatska Elektroprivreda, according to the aspects of application of the constructed ecological indicators, which are described in [26–30]. The similar technique of multivariate indicator construction were investigated in [31]. The paper estimates the environmental efficiency of 15 thermo power plants over the years. The environmental efficiency, defined as a function of consumptions, costs and emissions (SO_2, $NO_{x,}$ ash, and CO_2). However it uses different techniques for the estimation: "Multi Criteria Decision Making" and "Technique for Order Preference by Similarity to Ideal Solution".

The first section of this paper introduces the selected model of the integral indicator and requirements to the data table. The second section describes the non-supervised algorithms: Pareto slicing, Metric Algorithm and Principal Components Analysis. The third section describes the supervised algorithms based on expert estimations: Weighted sum, Expert-Statistical Method and Linear specification of expert estimations. The last section presents the Integral Indicator for the Croatian Power Plants.

2. Initial conditions

A set of m objects (power plants) and a set of n features (waste measurements) define the data table: the matrix $A\in\mathbb{R}^{m\times n}$, where an element $a_{ij}\in A$ is the value of the j-th feature for the i-th object. The row-vector $\mathbf{a}_i = [a_{i1},\dots,a_{in}]$ of the matrix A is a description of the i-th object. Let us call the vector $\mathbf{a}_i$ the object for short.

Let the integral indicator for the i-th object be the linear combination of the features

$$q_i = \sum_{j=1}^{n} w_j g_j(a_{ij}), \tag{1}$$

where g_j is a normalization function, which maps feature values into the unified scale:

$$g_j : a_{ij} \mapsto (-1)^{s_j} \frac{a_{ij} - \min_j (a_{ij})}{\max_j (a_{ij}) - \min_j (a_{ij})} + s_j. \tag{2}$$

The modifier $s_j\in\{0,1\}$. If the fraction (2) has zero in the denominator for some j, then the j-th feature cannot be used in the integral indicator and must be excluded from consideration. Without limitation of the applicability assume the following. The greater value of i-th object, given j-th feature, involves the greater value of the integral indicator for this object. This principle is called "the greater the better". The function g_j transforms values of the measured feature into values of the normalized feature, which satisfy the following conditions. First, values of the feature fit the principle "the greater the better". When $s_j = 1$ the optimal value of the j-th feature is minimal. Otherwise it is maximal. Second, g_j maps all values of the feature into the segment $(0,1)$ by the affine transformation so that all the features in the data table are comparable. When the condition (2) is satisfied, the model (1) can be represented as

$$q_i = \sum_{j=1}^{n} w_j a_{ij},$$

or for short,

$$\mathbf{q} = A\mathbf{w}, \tag{3}$$

where the integral indicators $\mathbf{q} = [q_1,\dots,q_m]^T$ and the feature weights $\mathbf{w} = [w_1,\dots,w_m]^T$. From the condition (2) it follows that the feature weights are positive. Since the integral indicator is expected to be an invariant to scaling, put an additional requirement to the weights: $\|\mathbf{w}\|_2 = 1$.

Thus, the matrix A must be prepared to satisfy the conditions above. This matrix must fit the concept "the greater the better". It means that an expert expects an object with the greater feature values has the greater, "the better", value of the integral indicator. An object of the maximum indicator is considered to be "the best" as well as a feature of the maximum weight is considered to be "the most important".

3. Non-supervised methods

The main goal of these methods is to provide the clear and reasonable way to construct the integral indicator with no expert