DEVELOPMENT OF ECO-EFFICIENCY COMPARISON INDEX THROUGH ECO- INDICATORS FOR INDUSTRIAL APPLICATIONS

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(Submitted: June 11, 2016; Revised: November 6, 2016; Accepted: November 13, 2016)

Abstract – In the last decades companies aligned with the concepts and principles of sustainable development have been seeking to minimize the environmental and social impacts caused by their operations. Typically, the primary environmental concerns in the industry were related to water consumption, wastewater production, waste generation, energy consumption and mainly CO₂ emission - which is one of the causes of the greenhouse effect. However, the environmental eco-efficiency is not clearly seen when the evaluations of these eco-indicators are individually used and, therefore, it becomes necessary to implement a methodology that enables a joint assessment involving various aspects. In this paper we have developed an environmental index, called Eco-efficiency Comparison Index (ECI), applied to evaluate in real time a petrochemical facility. Throughout a study-case based on experimental data, the results have evidenced that the ECI is a useful tool for eco-efficiency analysis for process monitoring.

Keywords: eco-efficiency, eco-indicator, industrial facility.

INTRODUCTION

The rise in global warming, energy consumption and gas emissions has been the object of investigation of several studies. There are numerous methods and indicators capable of describing environmental efficiency or some of its components. The approaches and principles of these practices and indicators vary due to differences in industrial applications and desired outcome.

According to the World Business Council for Sustainable Development (WBCSD), eco-efficiency is competitive in production and marketing of goods or services that satisfy human needs, improving the quality of life, minimizing environmental impacts and intensity of natural resource use and can consider the entire life cycle analysis (LCA) of production (WBCSD, 2000). Thus, it allows achieving the social, ecological and economic

parameters, aiming to reduce the consumption of resources (energy, water, materials, raw material, etc.). At the same time, eco-efficiency may minimize the impact on nature (water consumption, air emissions and dispersion of harmful substances) while maintaining and enhancing the value of the manufactured product (Maxine et al. 2006).

When addressing emissions and waste of a typical industry, such analysis is limited to only one of the elements in the entire chain (from the production to the delivery of the service to the user). However, life cycle analysis (LCA) is a broader study because a more detailed study can be made, showing a way of understanding the impact of different alternatives (Jollands, 2003).

Environmental indicators that aim to measure the eco-efficiency are tools used to condense information helping the engineers to make decisions. Different approaches for measuring eco-efficiency using eco-based indicators

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were introduced into the literature by Tyteca (1996). The eco-indicators are defined as an environment variable (i.e., consumption) divided by an economic variable (i.e., production or production cost) (Maxine et al., 2006; Siitonen et al., 2010). However, another way to calculate an eco-indicator is using the reciprocal of this form (Tahara et al., 2005; Kharel and Chamondusit, 2008), often replacing production by monetary income (revenue) as the economic variable.

Usually the eco-efficiency analysis is difficult when measurements are observed from a single eco-efficiency indicator. Thus, it becomes necessary to evaluate a set of indicators to provide a complete evaluation of an industrial process. However, it is worth emphasizing the difficulty in benchmarking when the indicators are used together (consumption of energy and water, wastewater and waste generation and CO₂ emission, for example). In this context, the indicators may not be enough to evaluate efficiency if they are presented separately. Given this, synthesize them as an index can be a useful solution.

Petrochemical plants are a relevant source of atmospheric emissions of carbon dioxide, carbon monoxide, methane, oxides of sulfur, oxides of nitrogen, etc. The petrochemical industry represents one of the most relevant industrial sectors in Brazil. Its production volume will tend to expand in the coming years with the construction of new petrochemical plants (Rio de Janeiro - COMPERJ; and others states of Brazil like Ceará, Pernambuco and Maranhão). Usually, the activities of the petrochemical industry consume significant amounts of energy and water and produce intrinsically CO₂ emissions to the atmosphere, as well as water wastes (effluents) and solid wastes.

Based on the previous remarks, this work aims to develop a global method to compare, in real time, the eco-efficiency of a petrochemical company. The goal is to construct a monitoring tool capable of summarizing in eco-efficiency indexes the main environmental aspects of the operational conditions and their primary environmental impacts, including global warming, photochemical ozone creation, soil acidification and human toxicity.

In the next section, the industrial applications of eco-indicators are briefly reviewed, and the concepts and methods for environmental construction tools are discussed. In the Methodology, the Eco-efficiency Comparison Index method is proposed. In sequence, the industrial petrochemical plant is briefly introduced. Subsequently, the results based on the process analysis are presented. Finally, we conclude the article, summarizing and suggesting remaining issues for future research.

LITERATURE REVIEW

Since some organizations began to be concerned about environmental issues, such as the realization of

“Our Common Future” in 1987 and “Agenda 21” (Rio de Janeiro, Brazil) in 1992, governments of many countries and organizations have emphasized the importance of the concept of sustainability. Such concept includes the integration of the economic, social and ecological pillars (Cote and Hall, 1995; Lowe and Evans, 1995; Charmondusit, 2009) and it allows fitting the needs of the present generation without compromising the ability to meet the needs of future generations. Furthermore sustainability integrated into performance management systems brings concrete innovations in organizational culture and processes as it prioritizes resources, monitors current activities and presents results of pursuing agreed targets.

Some eco-indicators focus on simple function between environmental and economic variables, generally used for industrial process monitoring; whereas other more sophisticated tools enable the joint utilization a set of eco-indicators (e.g., “Environmental Fingerprint” method) for analysis of different alternatives. Some of these tools are overviewed in the following sections.

Efficiency measurement

A range of methods has been applied to measure various efficiency concepts. Such strategies, therefore, can take many different forms according to the goal, object or system analyzed, and the methodology taken by researchers or practitioners. It can involve the use of Efficiency Indicators, Economic-Ecological Models, Simulation Modeling, Decomposition Analysis, Computable Equilibrium Models, Input-Output Analysis, Ecological Multiplier Analysis, Multiattribute Decision-making (MADM) and Complex Adaptive system Models (Jollands, 2003). Such methods are useful to measure efficiency in LCA; however, they can also be applied to measure eco-efficiency in a more restrictive way.

The Material Input per Unit of Service (MIPS) concept can be used to measure eco-efficiency of a process or product. The method takes into account materials required to produce a product or service in which the material input (MI) is divided by the number of service units (S) (Cahyandito, 2009).

According to Jollands (2003), Decomposition analysis is a powerful tool that provides the analyst with the ability to identify the key factors that effect eco-efficiency indexes. Studies have pointed out that principal component analysis (PCA) is a relatively accurate method, in that it reduces the number of data dimensions without much loss of information. However, such methods can suffer from rotational ambiguity, which means that different solutions may produce the same fit to the data matrix (Jollands, 2003).

Previous studies (Jollands, 2003) used Factor Analysis (FA) and Principal Components Analysis (PCA) together

with aggregate eco-efficiency indicators. According to the author, FA/PCA is a promising method, in that it reduces the number of data dimensions without much loss of information.

Wu et al. (2012) applied a new variant of Factor Analysis, the so-called Positive Matrix Factorization (PMF) to the problem of weighting and integrating eco-efficiency indicators. According to the authors, the results of PMF are guaranteed to be non-negative, while the results of FA often cannot be rotated to eliminate all negative entries.

In Woon and Lo (2006) a modified eco-efficiency indicator was developed to integrate the life cycle human health impact associated with two proposed waste disposal facilities. The modified index was based on a two-dimensional graph. The first dimension was calculated through the life cycle costing and the second one by the life cycle human health index. According to the authors, the modified eco-efficiency indicator involving environmental and economic aspects of the proposed facilities from a life cycle perspective facilitates the stakeholders in developing policy guidelines for pursuing an eco-efficient management.

Eco-indicators for eco-efficiency analysis

An eco-indicator is usually expressed in relative terms: a ratio between economic and environmental variables. Based on the works of Sittonen et al. (2010), Zhou et al. (2010), Liu et al. (2011), Zhang et al. (2012) and taking economic variables such as production, these eco-indicators can be defined as:

- Water Consumption - Ratio of the total water consumed in a period by the total production equivalent (m^3 / t).
- Energy Consumption - Ratio of total energy (all energy sources, including electricity) consumed in a period by the total production equivalent (GJ / t).
- CO_2 Emissions - Ratio of total CO_2 emissions (combustion, indirect and fugitive) in a period by the total production equivalent (t / t).
- Wastewater Generation - Ratio of the total effluents generated in a period by the total production equivalent (m^3 / t).
- Waste Generation - Ratio of the total solid waste generated in a period by the total production equivalent (kg / t).

The information and experience from both the high administrative sectors and factory employees who deal directly with the process are essential to collect data that can provide valuable information for the development of eco-indicators. However, an eco-indicator should not be analyzed separately but aggregated with other eco-indicators. Such eco-indicators may form an environmental index to evaluate the eco-efficiency. Thus, for a complete evaluation, the development of an environmental index for comparison of eco-efficiency is necessary.

In recent years researchers have found new ways to aggregate complex datasets including social-economical and environmental data. Proper selection of environmental indicators is the most important decision for the evaluation of the eco-efficiency of the industry (Nordheim and Barrasso, 2007). According to Veleva and Ellenbecker (2001), the construction of indicators should be based on five criteria. (i) The determination of the unit of measurement for calculating the indicator; (ii) the type of measurement (absolute - measure a total amount - or relative); (iii) the period of analysis; (iv) the development of objectives and (v) the targets and limits (how much a company wants to measure the indicators covered).

Aggregate indexes are potentially useful for indicating complex information succinctly to decision makers. It is possible to construct a general mathematical framework that accommodates the many options for aggregating eco-efficiency indicators instead of comparing directly input and output data. Such calculation consists of two fundamental steps: (i) calculation of the sub-indexes used in the final index; (ii) aggregation of the sub-indexes into the overall index. The aggregation function can involve summation, multiplication and maximum or minimum mathematical operations. Examples of aggregate indexes are Ecological Footprint/Fingerprint, Index of Sustainable Economic Welfare, Pollution Index, Unified Global Warming Index, etc. (Jollands, 2003). Their greatest contribution is the simplicity and ease of understanding for the policymaker unfamiliar with environmental issues (Ichimura, 2009).

The weighting step of an eco-efficiency analysis transforms and aggregates environmental inventory data, which can be a significant number of different parameters, to a single index. Many different weighting methods are used in industry. The main differences can be assigned to which reference for evaluation that is chosen, which principle is applied for the assessment and whose preferences the evaluation is based upon. Another important aspect is the spatial extension of the weighting method, i.e., for which geographic region the weighting method is compatible with. Different weighting methods have been used in industry: BASF, Eco-Indicator 99, Ecopoints, Environmental Themes, etc (Borén, 2008).

Eco-indicators for assessing eco-efficiency have been reported in the literature for some applications in industry, such as aluminum (Nordheim and Barrasso, 2007), iron (Kharel and Charmondusit, 2008), steel (Sittonen et al., 2010; Van Caneghem et al., 2010), iron and steel (Zhang et al., 2012), petrochemical (Charmondusit and Keartpanprae, 2011), ammonia (Zhou et al., 2010), calcium (Liu, et al., 2011), cement (Von Bahr et al., 2003) and sugar cane (Ingaramo et al., 2009).

The most recent papers are described below:

Rattanapan et al. (2012) developed eco-efficiency indicators involving economic and environmental indicators

based on material flow analysis. The result evidenced that economic indicators (consisting of product quantity and net sale) and environmental indicators (consisting of material consumption, energy use, water consumption, wastewater production, solid waste production and greenhouse gas emission) were capable of improving process productivity and enhancing recyclability or reducing energy and material intensity.

Park and Behera (2014) proposed an eco-efficiency indicator as a parameter for quantifying the economic and environmental performance of industrial networks. In their strategies, they included one economic indicator and three environmental indicators (raw material consumption, energy consumption, and CO₂ emission). The authors obtained an increase of 28.7 % of eco-efficiency. However, it was pointed out that the most significant limitation of the eco-efficiency evaluation is the availability and quality of the data required for calculations and that they may not represent the process behavior correctly in some cases.

In Silalertruksa et al. (2015) the eco-efficiencies of different sugarcane biorefinery systems for ethanol production were evaluated using two environmental and economic performance indicators. The proposed eco-efficiency was a useful indicator to compare the eco-efficiency of the different sugarcane biorefineries.

In Vukadinovic et al. (2016) eco-indicators were used to identify the retrofit opportunities to reduce the carbon intensity of power generation. The following eco-indicators were used: energy consumption, climate change, acidification, and

waste generation. All the indicators could be reduced: energy consumption, CO₂ emission and SO₂ emission.

Burchart-Korol et al. (2016) proposed an eco-efficiency assessment, life cycle assessment (LCA) and life cycle costing (LCC) of underground coal gasification. The authors identified that the largest impact on damage categories was caused by CO₂ emission from syngas combustion and electricity consumption.

In the Environmental Fingerprint approach, used by BASF Company, the ecological parameters are represented in the same coordinate system, providing comparative values of eco-efficiency and dismissing absolute values due their lack of representation in the analysis (Saling et al., 2002).

For illustration, the Fingerprint is plotted in the “radar” graphic, as shown in Fig. 1, and such as presented in the literature (Bidoki et al., 2006; Garcia-Serna et al., 2007). As seen, it is divided into six indicators for: Energy Consumption, Emissions (to air, water and wastes), Toxicity Potential, Risk, Material Consumption and Soil Use, available in dimensionless form.

Figure 1 shows that the indicators are available together, but it can be difficult to evaluate qualitatively the best alternative (1, 2, or 3) only by the geometric figure formed, especially when they are apparently similar. Thus, for the decision-making task for assessing eco-efficiency, BASF also uses the so-called “Portfolio”, which aggregates the information reported from Fingerprint and weighting factors specified according to a relevant criteria (i.e., scientific or social considerations).

Figure 1. Fictitious sample of the Fingerprint Method for three alternatives 1, 2 and 3.

METHODOLOGY

In the follow sections, we will describe the methodology for constructing the eco-efficiency index to be applied to evaluate the performance of a petrochemical plant.

General idea

As previously mentioned, eco-indicators can be grouped and standardized in dimensionless form. To this end, each environmental impact category is normalized such that the worst case in each category is specified with the value one and the others receive a relative value between zero and one (all the values in the same category are divided by the highest value of this category – worst case). So that it is possible to build radar graph that plays the role of an index and serves as a comparative tool. Thus, the performances of an industrial plant at a particular time can be compared against each other by the area of the polygon generated by the radar graph. In the polygon formed, each axis represents an eco-indicator from the same origin.

The dimensionless form (normalized) eliminates the effects of a measurement scale and allows the joint use of eco-indicators in the form of a single index. So, it is assumed that all the eco-indicators have the same weight because they are an integral part of the same process and reflect the operational conditions. Consequently, the worst normalized environmental indicator is 1 and the best value is closer to 0. Hence, the smaller the area, the better the environmental performance of the petrochemical plant in this period.

Graph radar area

The area of the polygon formed by the radar graph was calculated by the Law of Sines. The area is given by the sum of the areas of the n triangles in the graph; where n is the number of eco-indicators.

For this calculation, it is necessary to know the sides of the triangles (the eco-indicators represent the values of each axis of the radar graph) and the angle formed by the axis and its adjacent axis (so, all angles of the triangle are equal and known by value $2\pi/n$). The curve, which limits the graph joining points of the axis (axis values) represents the third side of each triangle, but has no significance for the calculation.

Fig. 2 shows the example of the above description of a pentagon ($n = 5$) formed by five triangles, angles of 72° ($2\pi/5$) arranged in the radar graph. The sides of the triangles are given by l_1, l_2, l_3, l_4 and l_5 , which are the values of the indicators from 1 to 5, respectively.

Law of sines

To calculate the area of the triangles, at least two sides and the angle between them have to be known, to use the

Law of Sines. Fig. 3 displays a triangle ABC of the sides l_A, l_B and l_C and the height denoted as h . θ is the angle formed by the sides l_A and l_B .

The area of the triangle ABC (S_{ABC}) can be calculated by Equation (1):

$$S_{ABC} = \frac{l_A \cdot l_B}{2} \cdot \sin \theta \quad (1)$$

Equation (1) represents the Law of Sines, and will be used in the proposed methodology. The eco-indicators for the radar graphic are given by the known sides and the central angle.

Calculation of the radar graph area

Applying Equation (1) on the triangle formed by the sides l_1 and l_2 in Figure 2, for example, leads to Equation (2).

$$S_{12} = \frac{l_1 \cdot l_2}{2} \cdot \sin \left(\frac{2 \cdot \pi}{5} \right) \quad (2)$$

In Equation (2) S_{12} represents the area of the triangle formed by sides 1 and 2. Repeating the procedure for triangles, $S_{23}, S_{34}, S_{45}, S_{51}$ and adding to S_{12} , it is possible to obtain the area of the pentagon (S_T) formed, as shown in Equation (3).

$$S_T = S_{12} + S_{23} + S_{34} + S_{45} + S_{51} \quad (3)$$

Thus the Eco-efficiency index for the eco-indicators is built. For n eco-indicators, the expression of eco-efficiency can be applied generally by Equation (4).

$$S_T = \frac{1}{2} \cdot \sin \left(\frac{2 \cdot \pi}{n} \right) \cdot \left(l_1 \cdot l_n + \sum_{i=1}^{n-1} l_i \cdot l_{i+1} \right) \quad (4)$$

For a qualitative comparison, it is necessary to evaluate the radar graph (indexes) of different periods, for example. According to this, it may be possible to judge whether there was any increase or decrease of the eco-efficiency over the periods. Thus, the graph with the largest area (S_T^*) is the worst environmental scenario.

The Eco-efficiency Comparison Index - ECI - is written according to Equation (5).

$$ECI = \left(1 - \frac{S_T}{S_T^*} \right) \cdot 100\% \quad (5)$$

The ECI tool can be extended to any number of eco-indicators and variations, and represents the contribution of this paper to the eco-indicators field.

PETROCHEMICAL FACILITY

In this paper the process will be described in a succinct manner. The process analyzed here is represented in Figure 4.

Figure 2. Representation of the polygon in a radar graph, for five categories of indicators.

The raw material (derived from petroleum) is sent to storage and then processed in a cracker unit, where the hydrocarbon chain reaction occurs, resulting in the desired products. Then, the resulting current is cooled and sent to a separation unit, where the separation of the desired petrochemical products by compression, reaction and distillation processes occurs. These products can be sent directly to the client or stored to be distributed later. Production is recorded daily and split up in accounting by ducts - totalized by meters (mostly mass type ones) - and by trucks (loaded in storage units) - totalized by weighing. Liquid (fuel oil) and gas fuels (natural gas, methane and impure hydrogen) are sent to the steam boiler along with the electric energy and other inputs (nitrogen, chemistry products and others) are used for the entire unit.

As seen in Fig. 4 the inputs are: raw materials and supplies of external energy (electricity and natural gas), the processing units (cracking and separation/reaction), and energy generation unit (boiler), which also receives supplies of internal energy (methane, impure hydrogen and residual fuel oil). The outputs are: products and byproducts, transportation trucks and several process valves and relief to flare (torch). It is possible to observe, also, the several sources of energy consumption and CO_2 emissions. The water, wastewater and solid waste are not presented here; details can be found in Pereira

Figure 3. Representation of any triangle ABC.

(2013). However, they were considered for monitoring. With all these variables it was possible to develop the industrial eco-indicators.

Environmental impact

In this section a complementary study involving the process environmental impacts is explained. LCA attempts to quantify the full range of environmental impacts associated with a product by considering inputs of resources and outputs of wastes and pollution. Typically, such analysis is made at each stage of the product's life, e.g. acquiring raw materials, production process, transport and consumer's use (Borén, 2008).

Figure 4. Overview of a petrochemical industry, the energy and CO₂ emission sources (based on Pereira, 2013).

In the petrochemical facility analyzed in this paper the ECI is related to the following possible consequences: (i) global warming (GW), (ii) soil acidification (SA), (iii) photochemical ozone creation (OC) and (iv) human toxicity (HT) (Altamirano, 2013).

To this end, the following equations were considered: environment impacts

$$GW = \sum_i GWp_i \cdot m_i \quad (\text{kg CO}_2 \text{ equivalent}) \quad (6)$$

$$SA = \sum_i SAP_i \cdot m_i \quad (\text{kg SO}_2 \text{ equivalent}) \quad (7)$$

where m_i refers to the mass (in kg per kg of oil) of an i^{th} substance and the subscript p denotes potential impact. A detailed discussion of such indexes can be checked in Altamirano (2013). Table 1 lists the values of each potential, ω_p , related to different substances i (CML, 2001).

As seen, Photochemical ozone creation (OC) for emission of substances to air is calculated using the reference unit, kg ethene (C₂H₄) equivalent. It is the result of reactions that take place between nitrogen oxides

$$OC = \sum_i OCp_i \cdot m_i \quad (\text{kg C}_2\text{H}_4 \text{ equivalent}) \quad (8)$$

(NO_x) and volatile organic compounds (VOC) exposed to UV radiation (Altamirano, 2013).

$$HT = \sum_i HTp_i \cdot m_i \quad (\text{kg 1-4 dichlorobenzene equivalent}) \quad (9)$$

Notice that $\theta_i = m_i / \text{CO}_2$ is the ratio between each substance in relation to CO₂, as shown in Table 2.

In order to calculate the GW, SA, OC and HT provoked by the petrochemical facility, we have considered the data of a typical Brazilian petrochemical facility (Altamirano, 2013), summarized in Table 2.

Table 2 lists the global emission of a typical Brazilian petrochemical facility. Although such values might be different for distinct plants, those data were used as reference for a comparative study involving the indexes represented by Equations (6)-(9) for the present industrial plant. Wastewater and waste generation are not listed because they do not affect the indexes GW, SA, OC and HT

Table 1. Impact coefficients, ω , (CML, 2001).

Atmospheric emissions	GWp (kg CO ₂ equivalent) /kg	OCp (kg C ₂ H ₂ equivalent) /kg	SAp (kg SO ₂ equivalent) /kg	HTp (kg 1-4 dichlorobenzene equivalent)/kg
CO ₂	1			
CH ₄	21	0.006		0.006
CO		0.0147		0.027
N ₂ O	310		7	
NH ₃			1.88	0.1
NO _x			0.7	
Hydrocarbons		0.416		
Particulate Material				0.82
SO _x		0.125	1	0.048
H ₂ S			1.88	0.22
HCl			0.88	0.5
Dichloromethane	9	0.068		
HF			1.6	
Dimethyl ether	1	0.214		0.189
Methanol		0.14		0.14
Ethanol		0.399		0.399
Cyclohexane		0.29		0.29

(CML, 2001) sufficiently.

Tables 1 and 2 allow calculating the indexes described by equations 6-9. As observed in Table 2, carbon dioxide is the most representative component in the atmospheric emission. Thus, we have considered CO₂ as the key component to compute the quantity of the other substances. According to our results, discussed in the next topic, the CO₂ emission can vary with respect to the analyzed period. Thus, to quantify the amount of each component, the CO₂ (t/t) emission of each period is multiplied by the standard CO₂ emission listed in Table 2. In this way, the proportion of the other substances in relation to CO₂ is kept constant, being estimated indirectly.

RESULTS

For the present analysis, data were collected from a petrochemical plant for seven consecutive months from February to August, 2013. The data acquisition structure was implemented at the plant site based on Pereira (2013). Measured data were sent from the Digital Control System (DCS) to an EXCEL® spreadsheet with the help of an EXCEL® macro with samples of 1 minute. The industrial data were previously filtered (miscommunications, negative values and corrupted data) and the daily values of each eco-indicator were then developed by calculating the amount (generation or consumption) of the environmental parameters, based on mass and energy balances, and divided by the amount of produced products. Table 3

summarizes the analyzed periods.

The results section is divided in two parts: process monitoring and eco-efficiency analysis.

Process monitoring results

The month of June has been selected to show how eco-indicators are used for the daily monitoring process. In the next eco-indicators figures the last plotted result is the accumulative monthly value (Ac.) and it represents the total of generation or consumption divided by the total of the corresponding production.

Figs. 5 and 6 illustrate the eco-indicator of Energy Consumption and the Energy Matrix distribution in June 2013, respectively. The target represented in the figures denotes the operational objectives for a respective production period. Such value is usually defined by the manager team of the facility. The energy matrix is composed by: methane, impure hydrogen (mixture of hydrogen and methane), natural gas, electricity and residual fuel oil.

As seen in Fig 5, the energy consumption eco-indicator, on June 2nd, reached the target value of 22.5 GJ/t. It is also possible to observe that the target value was reached on June 13th, 15th, 16th, 17th, 21st, 26st, 27th, 29th and 30th.

Fig. 6 pictures the energy matrix of the month of June. As observed, the energy matrix is well distributed, including the fuel oil consumption produced at the site plant. However, it is observed in Fig. 7 that the CO₂ emission eco-indicator was very high (over the target

Table 2. Emissions of a typical Brazilian petrochemical facility (Altamirano, 2013).

Atmospheric emissions	kg / kg processed oil	Θ (in relation to CO ₂)
CO ₂	2.00E-01	1.00E+00
CH ₄	6.20E-02	3.10E-01
CO	9.10E-03	4.55E-02
N ₂ O	4.40E-06	2.20E-05
NH ₃	3.60E-13	1.80E-12
NO _x	3.00E-04	0.00E+00
Hydrocarbons	1.57E-05	7.85E-05
Particulate Material	0.00E+00	0.00E+00
SO _x	2.40E-03	1.20E-02
H ₂ S	9.00E-07	4.50E-06
HCl	9.00E-08	4.50E-07
Dichloromethane	0.00E+00	0.00E+00
HF	0.00E+00	0.00E+00
Dimethyl ether	0.00E+00	0.00E+00
Methanol	0.00E+00	0.00E+00
Ethanol	0.00E+00	0.00E+00
Cyclohexane	0.00E+00	0.00E+00

value of 0.99 t/t, defined by the manager team of the facility). It can be explained by the failure in the specification of the products, requiring delivery of part of the production to flare. Such result can be confirmed in Fig.8, which highlights the high percentage of CO₂ emissions to flare on June 21st and 26th. As seen, when the online analysis is over the set point values (safe and specification conditions) the relief valves are opened. An error in the automation control system was considered after this month. These are two examples of eco-indicators used every day in industry for process monitoring and decision making tasks highlighted in Figs. 5 and 7.

Figs. 7 and 8 illustrate the eco-indicator of CO₂ Emission and the CO₂ Emissions Matrix distribution in June, 2013, respectively. The CO₂ Emissions matrix is composed of the same elements of the energy matrix, plus the relief to flare emission. A modeling study for all relief valves to flare in this plant has been developed. Thus, given a valve opening, it was possible to estimate the mass flow through the valve and its corresponding amount in CO₂ to atmosphere.

To complete the process monitoring study Figs.9-11

show the Water Consumption, Wastewater Generation and Waste Generation eco-indicators developed, respectively.

Operational conditions reflect on all eco-indicators. On June 15th and 16th the eco-indicators presented high values due to the temporary reduction in production for inventory adjustment, as shown in Figs. 5, 7, 9-11.

Fig. 11 evidences that the waste is not removed daily. It is performed as operational logistics in function of the waste accumulation and traffic of trucks in the neighborhood of the plant site. Further details about these eco-indicators for seven months of monitoring can be found in Pereira (2013).

Based on the above results, an eco-efficiency comparison index (ECI) has been developed for process monitoring and decision-making tasks in the petrochemical plant.

Eco-efficiency results

This section presents all monthly accumulated results for each eco-indicator and also the normalized ones in order to evaluate the eco-efficiency among different periods. Table 4 summarizes all results for each month.

Table 3. Summary of the evaluation periods.

Periods	Description	Months
I	Period of observation and setting targets based on historical data. It corresponds to monitoring before the implementation of the methodology.	February and March
II	Initial phase of implementing of the method. Started focusing on eco-efficient measures to improve sustainable development.	April, May and June
III	Period wherein the method is implemented and functional. Monitoring phase of the methodology.	July and August

Figure 5. Eco-indicator of Energy Consumption (June).

Figure 6. Energy Matrix (June).

Figure 7. Eco-indicator of CO₂ emissions (June).

Figure 8. CO₂ Matrix (June).

Figure 9. Eco-indicator of Water Consumption (June).

Figure 10. Eco-indicator of Wastewater Generation (June).

Figure 11. Eco-indicator of Waste Generation (June).

Table 4. Eco-indicators and index results for each month.

Eco-indicators	February	March	April	May	June	July	August
Energy Consumption (GJ/t)	25.587	26.454	24.650	24.592	21.741	22.438	21.050
CO ₂ Emission (t/t)	1.234	1.270	1.132	1.139	0.979	1.010	0.932
Water Consumption (m ³ /t)	5.560	5.617	5.190	5.081	5.135	4.959	4.962
Wastewater Generation (m ³ /t)	1.611	1.885	1.622	1.608	1.528	1.499	1.508
Waste Generation (kg/t)	5.086	4.926	4.003	4.056	3.903	4.397	4.161
Energy Consumption (adm)	0.967	1.000	0.932	0.930	0.822	0.848	0.796
CO ₂ Emission (adm)	0.972	1.000	0.891	0.897	0.770	0.795	0.733
Water Consumption (adm)	0.990	1.000	0.924	0.905	0.914	0.883	0.883
Wastewater Generation (adm)	0.855	1.000	0.860	0.853	0.811	0.796	0.800
Waste Generation (adm)	1.000	0.969	0.787	0.798	0.767	0.865	0.818
Index (polygon area - S_p)	2.173	2.348	1.835	1.825	1.584	1.664	1.543
ECI	7.43%	*	21.83%	22.25%	32.51%	29.12%	34.29%

* Reference (worst case scenario - S_p).

By observing Table 4 it is clear that the two first months after the production startup were far from the optimal condition. It is possible to note that the ECI increased after March, achieving the highest value in August. However, as observed, in July the eco-indicators of Energy Consumption and CO₂ emission increased their values. It was the consequence of the combined factors:

- Sudden unavailability of raw material from external supplier and low storage levels on 17th July;
- Obstruction of one of main heat exchangers and plant intervention maintenance on 18th July;

To maintain the plant operating it was necessary to send to relief valves a considerable amount of processed material and adjust the production to another safe stationary state condition.

These problems are illustrated by the eco-indicator of

CO₂ emission in Fig. 12.

Table 4 also reveals that March corresponds to worst case scenario with 2.348 Index value. The comparison between March and August based on the ECI method shows that the eco-efficiency increased 34.29%. Other comparison results can also be found in Table 4. To better present the ECI method, Fig. 13 shows the accumulative results for the eco-indicators for the periods I, II and III, respectively, as discussed in Table 3.

Fig. 13 shows the increase of the eco-efficiency period after period by the radar graph area decreases. As expected, Period I (February and March) showed the highest values (1.0).

Table 5 evidences the increase of ECI results from Period II (April, May, June) to Period III (July and August). As observed, period I corresponds to the worst case scenario with 2.378 Index value. The comparison between Period I and Period III results based on the ECI

Figure 12. Eco-indicator of CO₂ emissions (July).

Table 5. Eco-indicators and index results for each period.

Eco-indicators	Period I	Period II	Period III
Energy Consumption (adm) 1.000		0.909	0.836
CO ₂ Emission (adm)	1.000	0.865	0.775
Water Consumption (adm)	1.000	0.919	0.888
Wastewater Generation (adm)	1.000	0.906	0.859
Waste Generation (adm)	1.000	0.797	0.855
Index (polygon area - S_T)	2.378	1.836	1.687
ECI	*	22.77%	29.06%

* Reference (worst case scenario - S_T^*).

method indicates that the eco-efficiency increased 29.06%.

The results of the Period III, when the ECI presented the best value, can be explained by the fact that some actions were taken together with the operational team:

- Meetings of multidisciplinary teams for better decision making tasks;
- Engagement of the people, especially the operation team;
- Local improvements;
- Adjust the control loops on product specification issue for relief to flare;
- Adjust the online chromatograph meter for accuracy measures;
- Adjust the control loops on security issue for relief to flare;
- Detection of leaks in the cooling water and wastewater systems;
- Detection of leaks in steam lines.

With the eco-indicators, it was possible to observe the production process widely and locally, seeking eco-efficient improvements.

Environmental impact results

Analysis of the GW, SA, OC and HT indexes can be checked in Figure 14 and Figure 15. As observed, CO₂ emission is the major cause of global warming, as expected. As seen, the environmental impact indicators (OC, SA and HT) also decrease with the reduction of CO₂ emission. Such analysis agrees with the data listed in Tables 1 and 2 because the ratio of each substance in relation to CO₂ is considered constant in our analysis. Therefore, the profiles present the same tendency.

The results of Figures 14 and 15 also clarify that the environmental impact could be decreased, principally after the actions taken in period III. Such results highlight the importance of process monitoring, which was possible after the implementation of the ECI.

In order to evaluate the impact of each substance over GW, OC, SA and HT, a sensitivity analysis was done. The results are presented in Figures 16, 17, 18 and 19.

For sensitivity analysis we considered the complete individual reduction of the most critical substances (CH₄, CO, NO_x, and SO_x keeping CO₂ constant) in relation to the

Figure 13. Eco-efficiency analysis by the ECI method for three distinct periods.

Figure 14. Environmental impact (OC, AS and HT) profiles (the dark region corresponds to the period III).

Figure 15. Environmental impact GW profile (the dark region corresponds to the period III).

standard CO₂ levels presented in Table 2. Such study was conducted for the period I.

The summary of the results illustrated in Figures 16, 17, 18 and 19 evidences that:

- The global warming (GW) may be reduced by minimization of CH₄;
- The ozone creation (OC) may be reduced by minimization of CH₄, CO and SO_x;

Figure 16. Effect of CH₄ reduction over (a) GW, (b) SA, (c) OC, and (d) HT for Period I (0% - 100% of substance emission in relation to Table 2).

Figure 17. Effect of CO reduction over (a) GW, (b) SA, (c) OC and (d) HT for Period I (0% - 100% of substance emission in relation to Table 2).

Figure 18. Effect of NO_x reduction over (a) GW, (b) SA, (c) OC and (d) HT for Period I (0% - 100% of substance emission in relation to Table 2).

Figure 19. Effect of SO_x reduction over (a) GW, (b) SA, (c) OC and (d) HT for Period I (0% - 100% of substance emission in relation to Table 2).

- The soil acidification (SA) may be reduced by minimization of NO_x and SO_x ;
- The human toxicity (HT) may be reduced by minimization of CH_4 , CO and SO_x .

Based on the above results, several recommendations are made to improve the eco-efficiency of the studied petrochemical plant:

- Plant use of non-carbon-based energy sources;
- Reducing the carbon content from fuels;
- Increase the efficiency of heat and power production;
- Reducing the amount of wastes flared (Replacing the valves with greater probability of leakage);
- CO_2 capture technologies, such as cryogenic techniques;
- Replacement of the burners of the boiler to allow for burning liquid fuel - fuel oil, byproduct of the process with no great commercial value, in other words, change in the energy matrix, decreasing the importation of natural gas (external fuel with high monetary cost);
- Best advantage of recyclable waste, lowering disposal;
- Plant process optimization. The ECI may be used as objective function because it includes several indicators in a unique function). Furthermore, the environmental impact indexes may be used as constraints of the optimization problem.
- Implementation of data reconciliation for real time data acquisition (Prata et al, 2010).

CONCLUSIONS

Usually, environmental eco-efficiency is not clearly observed when measurements are performed with a single eco-efficiency indicator or indicators evaluated individually. Therefore, there is a need to develop methods for evaluating the eco-indicator integration, so as to reveal the state of a system or phenomenon and provide a tool for decision-making tasks.

The purpose of the paper was to analyze the eco-efficiency of a petrochemical plant, suggest eco-efficiency indexes for measurement of gas emissions, energy loss, and water waste and propose a global eco-efficiency index making use of experimental industrial data. The results indicate that some actions taken with the operational team of the facility could improve the facility eco-efficiency, e.g.: (i) meetings of multidisciplinary teams for better decision-making tasks; (ii) reducing the amount of wastes flared, (iii) avoid leaks in steam lines, (iv) replacement of the burners of the boiler etc.

An important contribution of this work is certainly developing the methodology for monitoring and process improvement and standardization of eco-indicators in an industrial unit. The development of the comparison tool, which covers all different ecological indexes, resulting in what has been called eco-efficiency comparison index -

ECI, allows evaluating the environmental performance in different periods.

Also, a supplementary study was done, evaluating the impacts of atmospheric emissions on the environment: (i) global warming (GW), (ii) soil acidification (SA), (iii) photochemical ozone creation (OC) and (iv) human toxicity (HT). It was possible to note that global warming is the main impact caused by the petrochemical industry, and the associated gasses (SO_x , CO and NO_x) are extremely related to the above indexes.

For future studies we suggest: (i) to develop real-time optimization tools, involving eco-indicators as the objective function, allowing optimizing of petrochemical facilities in a more global way, (ii) development of new eco-indicators with different weighting factors, considering environmental impacts, such as reducing human toxicity.

NOMENCLATURE

h - Height of the triangle.

ECI - Eco - efficiency Comparison Index.

l_1 - 1st axis of the radar graph representing the sides of the triangle.

l_2 - 2nd axis of the radar graph representing the sides of the triangle.

l_3 - 3rd axis of the radar graph representing the sides of the triangle.

l_4 - 4th axis of the radar graph representing the sides of the triangle.

l_5 - 5th axis of the radar graph representing the sides of the triangle.

l_A - Side (A) of the triangle.

l_B - Side (B) of the triangle.

l_C - Side (C) of the triangle.

n - Number of eco - indicators.

S_{12} - Area of the triangle that composes the polygon of the radar graph (axes l_1 and l_2).

S_{23} - Area of the triangle that composes the polygon of the radar graph (axes l_2 and l_3).

S_{34} - Area of the triangle that composes the polygon of the radar graph (axes l_3 and l_4).

S_{45} - Area of the triangle that composes the polygon of the radar graph (axes l_4 and l_5).

S_{51} - Area of the triangle that composes the polygon of the radar graph (axes l_5 and l_1).

S_{ABC} - Area of triangle ABC of sides l_A , l_B and l_C .

S_T - Total area of the polygon formed in the radar graph.

S_T^* - Total area of the polygon formed in the radar graph - worst case scenario.

θ - Angle formed by the sides l_A and l_B .

ACKNOWLEDGEMENT

The authors thank CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) for supporting our work and for providing scholarships.

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