The Environmental Dynamic Efficiency Of Onshore Oil Fields Located At The Brazilian Coastal Basin

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ABSTRACT

One of the main environmental concerns associated with the exploration and production of oil fields is related to the generation of produced water, this is a strategic challenge for companies since is resposible for the largest share of waste genretared by the oil industry. This theme is presented as multidisciplinary since it is a study with dynamic models in an environmental area linked to the oil industry. Thus, the present work aims to evaluate the performance of dynamic environmental sustainability, from the generation of produced water from onshore oil fields located at the coastal basins of Brazil with higher oil production. The data were made available by the ANP (National Petroleum Agency) from its website, totalizing 67 fields during the years 2014, 2015 and 2016. In addition, dynamic Data Envelopment Analysis was used to determine dynamic efficiency. The results showed a positive effect of the variables directional wells, vertical wells and age, the first two variable showed a fundamental role in determining environmental efficiencies. Therefore, the results allowed to state that there is a poor management of the technological resources in onshore fields of the Brazilian coastal basins, generating excessive amounts of produced water.

Keywords: Environmental sustainability. Oil fields. Environmental efficiency. Produced water.

1. INTRODUCTION

Nowadays, oil can be considered the most important source of energy, since it produces multiple derivatives (gasoline, kerosene, bitumen, etc.) in order to meet an ever increasing demand from society. According to data from the IEA (International Energy Agency), it is estimated that in 2018, the daily demand for oil reached the level of 146.2 million barrels per day worldwide. Despite this latent growth in oil production, there is an important trade-off in this production system between the development of the oil sector and the increase of waste generation inherent to the process, representing threats to the environment and environmental sustainability of this industry.

The oil and gas production processes produce large volumes of liquid waste, among which stands out the generation of produced water. This term is used to describe a water that is produce along with oil and gas during production, that is often injected into wells in order to increase oil recovery (Venkatesan & Wankat, 2017)

This undesirable fluid is an inextricable part of the hydrocarbon recovery process. As the fields develop, they tend to produce increasing amounts of water (Khatib & Verbeek, 2003), and can reach values close to 100% of the well's production as it reaches the end of its productive life.Thus, in view of the problem exposed it is evident the damage caused to the environment due to the repeated and constant generations of water produced by the oil and gas industry, promoting damage to the environmental sustainability of the industry, generating challenges for researchs for efficiency.

One of the most used techniques to measure the efficiency of a set of decision units is Data Envelopd Analysis (DEA), whose application has spread through several areas, assisting in decision-making for greater efficiency (Liu, Lu, Lu & Lin, 2013). The DEA uses a non-parametric method, whose objective is to determine the efficiency curve from a mathematical optimization schedule, allowing to analyse the relative performance of similar production units (Cook & Seiford, 2009).

Considering the relevance of this theme, it was identified the scarcity of quantitative studies related to the evaluation of productive efficiency in the oil and gas industry, especially with the consideration that the production system has an undesirable output, the "produced water". Through the importance and impact of environmental issues on the oil industry, this study continues the considerations of Song, Zhang & Wang, 2015, Sueyoshi & Goto, 2012 and Sueyoshi & Goto, 2012a.

However, this is a distinct analysis, since it aims to investigate the dynamic aspects of production through an adequate modeling (DDEA), in order to monitor the environmental performance of productive fields of the Brazilian coastal basins for both productive and environmental issues, showing the multidisciplinarity of this theme. This transversality of knowledge brings to the end the need to research about the themes that use multiple sciences for their development, as can be attested in the case of the environment area.

Therefore, this work aims to evaluate the dynamic environmental efficiency of oil fields located at the Brazilian coastal basins, considering the years 2014, 2015 and 2016, through Data Envelopment Analysis (DEA). This evaluation was structured in the considerations of Golany & Roll (1989), characterized by constant returns of scale and product orientation. Moreover, this study seek to promote a significant contribution to specialized literature regarding the oil and the environment area, since it deals with an environmental efficiency model capable of measuring the performance of an oil field focusing on the output of an undesirable product: produced water. In addition to the contribution related to the environmental area, the study contributes to the literature of DEA, since studies using it in the oil sector are still insipid, especially with the use of dynamic models.

2. EFFICIENCY MODELS APPLIED TO THE OIL INDUSTRY

Industrial development is important to all nations when evaluating their economic prosperity. However, this development causes trade-offs among which stand out: air pollution, water and other types of contamination, that result in health problems to the population and climate change. Thus, it is necessary to consider how to reach a balance between economic success and pollution mitigation to maintain a high level of social and environmental sustainability worldwide (Sueyoshi, Yang & Goto, 2017).

In order to better understand these socioclimatic changes and seek for the best practices of environmental sustainability, Sueyoshi, Yang & Goto (2017) systematized a broad research from the world theoretical framework in the area of energy and environment, being it dividedin the areas of energy and environment for a better methodological segmentation.

The energy area was subdivided into three sub-areas (electricity; oil, gas and coal; renewable energy). The oil and gas subarea, focus of this work, presented a quantity of 23 studies since the 1980s and only 9 with a focus on environmental efficiency, shown in Chart 1.

Chart 1 - Variables used by the work on efficiency models applied to the oil industry

		Bevilacqua, Braglia (2002)	Mekaroonreung; Johnson	Sueyoshi;Goto (2012)	Sueyoshi; Goto (2012a)	Ismail; Tai; Kong; Law;	Oke; Kareem (2013)	Francisco;	Sueyoshi; Wang (2014)	Song; Zhang;
Inputs	Produced oil	●								
	Capital		●			●	●			
	Consumed energy		●							
	Assets						●			
	Age									
	Total current assets								●	●
	Total non-current assets									●
	Impairment loss of assets									●
	Costs								●	
	Drilled wells								●	
	Vertical wells									
	Directional wells									
	Crude oil		●							
	Water consumption							●		
	Oil reserve			●	●					
	Idleness							●		
	Gas reserve			●	●					

	Cost				●	●					
	API Grade										
	Manpower				●	●	●			●	
Outputs	Desirable	Oil production			●	●			●		
		Gas		●							
		Distilled		●							
		Gas Production			●	●					
		Profits					●	●		●	
	Undesirable	Gas emission	●		●						
		Produced water									
		Toxic or effluent		●					●	●	
	Uncontroll	Age of refinery							●		
Country			Italy	USA	USA	USA	Multiple Countries	Nigeria	Brazil	USA	China
Number of DMU's			28	113	19	19	17	5	10	50	20
Model			CCR	Hiperbólico	CCR/ DTS*	CCR/DTS *	CCR/ Ecoeficiên	CCR/BCC	CCR/ BCC	UE/ UEN /UEM	DEA

Source: Research data, 2020.

**Disposability and Damages to Scale (DTS)*

Bevilacqua & Braglia (2002) assessed the relative environmental efficiency of the seven oil refineries created in Italy over a 4-year period (1993-1996), considering six different types of emissions (CO, CO_2, SO_2, NO_x, TSP, VOC)) as undesirable outputs and the annual amount of oil processed as inputs. The results showed that refineries containing an environmental management system present better efficiencies.

The work of Mekaroonreung & Johnson (2010) aimed to describe and compare various methods in order to estimate the technical efficiency of 113 oil refineries operating in the United States between 2006 and 2007, considering the emission of toxic gases as an undesirable output. A hyperbolic efficiency measure was applied to analyze the potential loss of each refinery due to environmental regulations. The results indicated that domestic refineries could improve efficiency, regardless of disposal assumptions, and that environmental regulations would reduce the amount of potentially desirable products produced by some facilities.

Also in relation to the American reality, Sueyoshi & Goto (2012, 2012a) used the DEA to perform an environmental assessment using non-radial DEA models in 19 oil companies: 14 American and 5 foreign. This study proposes three types of unification for environmental assessment of the DEA. The results denoted greater efficiency for foreign companies, especially those from Saudi Arabia and Russia. Another conclusion obtained was that the national oil companies would need to meet their own country's environmental standard, while international oil companies should comply with international standards stricter than national standards.

The reality of the Nigerian oil industries was studied by Oke & Kareem (2013) in order to investigate the operational efficiency of five oil companies, taking as reference the years from 2006 to 2009. The application of the DEA CCR and the BBC was used for data analysis. The research found that two companies operated below 10% of operational efficiency, causing an average efficiency of the companies studied below 50%.

Ismail, Tai, Kong, Law, Shirazi & Karim (2013) designed a study focusing on analyzing the environmental performance and economic efficiency of the global operations for 17 companies in 2008. These companies were selected from the global oil industry by applying a comparison between technical efficiency and eco-efficiency. The results showed a weak positive relationship between eco-efficiency and technical efficiency in relation to the companies studied.

Song, Zhang & Wang (2015), took advantage of the DEA in networks to develop an environmental efficiency model for 20 companies from the Chinese oil industry,, being compared the results of pollutant treatment efficiency and production efficiency between years 2006 and 2011.

The same market approach adopted by Song; Zhang & Wang (2015), related to the Chinese oil market, was used by Sueyoshi & Goto (2015). They considered 17 companies in the oil sector to calculate the environmental efficiency index under evaluation from 2006 to 2009, evolving the model proposed by Sueyoshi & Goto (2012, 2012a), since the malmquist index was included for this study. They concluded that the industry did not exhibit any major boundary change over the evaluated years. When considering companies, they saw a considerable boundary change under the capacity to manage and improve environmental performance.

Thus, following the trend of studies in refineries (Sueyoshi & Goto, 2012, 2012a), an environmental efficiency assessment, with emphasis on effluents and water consumption in the production process for 10 refineries from the Brazilian public sector was carried out by Francisco, Almeida & Silva (2013). The classical methods of DEA (CCR, BCC) were applied in this research, considering a model of desirable outputs and two others with undesirable outputs. Based on the comparison of the results, it was verified the clear importance of the environmental variable for a more accurate analysis of the production process and the rejection of the hypothesis that the age of the refinery would negatively interfere in production.

Sueyoshi & Wang (2014) proposed a corporate sustainability measure to reduce undesirable outputs (e.g. CO_2) through DEA. The study was conducted using data from 50 companies (integrated and independent companies) from the oil sector of the United States. It was evidenced that integrated companies overcome the independent due to the large supply chain incorporated into the first group provided them a scale of merit in their operations as well as an opportunity to gain consumer opinions about their business operations. Thus, the large supply chain system, which covers upstream and downstream business functions, would increase corporate sustainability in the U.S. oil industry.

Tavana, Khalili-Damghani, Arteaga & Hosseini (2019) presented a multi-objective, customized DEA model to evaluate the dynamic performance of oil refineries in the presence of undesirable results, with an application in 9 refineries located in the United States.

Hu,Yan, Li, Yao & Feng (2020) developed a Network DEA model focusing on the production of produced water. The Stage 1 is related to oil development while Stage 2 is associated with wastewater treatment. Thus, considering that the model needs to solve undesirable results, a Data Envelopment Analysis (DEA) Slack-Based Static Measurement (SBM) network structure model with a feedback variable was established. Furthermore, a total of 13 oil fields were used and the results state there is a stronger relationship between the efficiency of oilfield wastewater treatment and the entire system.

Few studies have been developed regarding the application of DEA in the oil industry focousing on the environmental efficiency, most studies investigated the reality of the American oil industry through the use of classic Models of DEA (CCR and BCC), making clear the need for development for this theme to the use of more complex and robust models - hybrid, dynamic and in networks - already developed.

3. RESEARCH METHOD

This study is characterized as quantitative and exploratory, since it performed an evaluation of the efficiency for 67 oil fields (with oil production below 14000m^3/year) located at the basins of Alagoas, Espírito Santo, Potiguar and Sergipe. For this, secondary data from National Petroleum Agency (ANP) were collected for the years 2014, 2015 and 2016.

This sample cut-out made it possible to obtain a more homogeneous set of DMU's, which allowing the use of the DEA tool, which presupposes homogeneity of the DMU's in order to ensure adequate results.

The study carried out by Dyson, Allen, Camanho, Podinovski & Sarrico (2001) discusses in depth the issues related to homogeneity in DEA and how to ensure it. Data Enveloping Analysis (DEA) was chosen because it is a method capable of measuring, with greater robustness, the efficiency of a set of DMU's related to environmental sustainability issues (Sueyoshi & Goto, 2017).

The modeling adopted in the investigation corresponds to the dynamic model of DEA, once that the research seeks to evaluate a three-year time frame. Thus, since it aims to understand the variations by period and total of productive efficiency, the modeling proposed by Kao (2013) described in Equation 1, was elected as the most appropriate for the reality explored in this work.

$$\frac{1}{E_k^R} = min. \sum_{i=1}^{m} v_i . X_{ik} + \sum_{f=1}^{g} w_f . Z_{fk}^{(0)}$$

$$s.t. \sum_{r=1}^{s} u_r . Y_{rk} + \sum_{f=1}^{g} w_f . Z_{fk}^{(p)} = 1$$

$$\left(\sum_{f=1}^{m} v_i . X_{ij} + \sum_{f=1}^{g} w_f . Z_{fj}^{(0)} \right) - \left(\sum_{r=1}^{s} u_r . Y_{rj} + \sum_{f=1}^{g} w_f . Z_{fj}^{(p)} \right) \geq 0, j = 1, \ldots, n$$

$$\left(\sum_{i=1}^{m} v_i . X_{ij}^{(t)} + \sum_{f=1}^{g} w_f . Z_{fj}^{(t-1)} \right) - \left(\sum_{r=1}^{s} u_r . Y_{rj}^{(t)} + \sum_{f=1}^{g} w_f . Z_{fj}^{(t)} \right) \geq 0$$

$$j = 1, \ldots, n; \quad t = 1, \ldots, p \qquad (1)$$

$$u_r , v_i , w_f \geq \varepsilon, r = 1, \ldots, s; \quad i = 1, \ldots, m; f = 1, \ldots, g$$

Where v_i is the usefulness of input; u_r is the output utility; w_f is the usefulness of the intermediate product; X_{ik} is the amount of input i for DMU k; Y_{rk} is the quantity of product r for DMU k; $Z_{fk}^{(p)}$ is the amount of the intermediate product f for DMU k in period p; $Z_{fj}^{(p)}$ is the amount of the intermediate product f for DMU j in period p; Z_{fk}^{0} is the quantity of the intermediate product f for DMU k that is the imput in the initial period; Z_{fj}^{0} is the quantity of the intermediate product f for DMU j that is entered in the initial period; X_{ij}^{t} is the amount of input i of DMU j in the period under analysis; Y_{rj}^{t} is the quantity of product r in the DMU j for the period; Z_{fj}^{t-1} is the quantity of the intermediate product f for DMU j in the period prior to that the one under analysis; and, Z_{fj}^{t} the quantity of the intermediate product f of DMU j in the period under analysis.

With the optimal solution (u_r^*, v_i^*, w_f^*), one can calculate the efficiency of the whole system, E_k^s, and period, $E_k^{(t)}$, with t = 1,..., p, for DMU k, using Equations 2 and 3, based on the second and third sets of constraints of the model previously exposed:

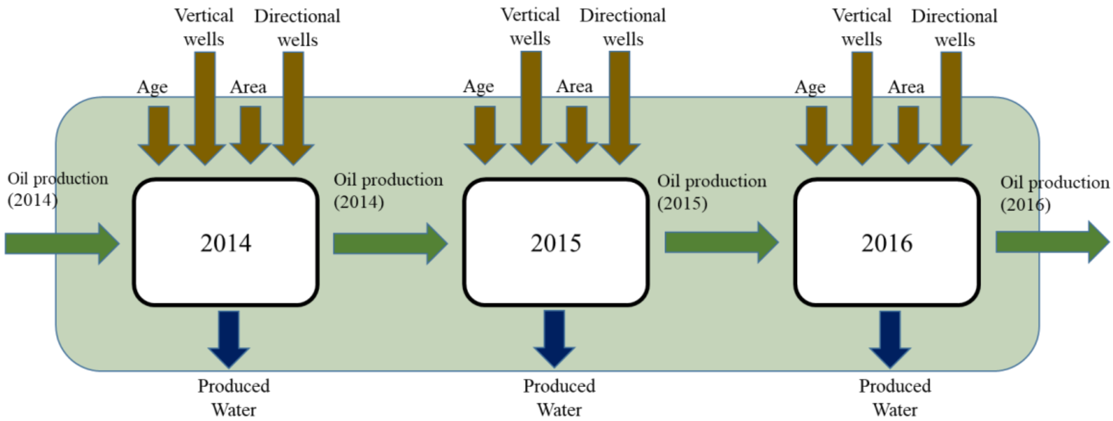
$$E_k^S = \frac{\sum_{r=1}^{s} u_r . Y_{rk} + \sum_{f=1}^{g} w_f . Z_{fk}^{(p)}}{\sum_{i=1}^{m} v_i . X_{ik} + \sum_{f=1}^{g} w_f . Z_{fk}^{(0)}} \quad (2)$$

$$E_k^t = \frac{\sum_{r=1}^{s} u_r . Y_{rk}^{(t)} + \sum_{f=1}^{g} w_f . Z_{fk}^{(t)}}{\sum_{i=1}^{m} v_i . X_{ik}^{(t)} + \sum_{f=1}^{g} w_f . Z_{fk}^{(t-1)}} \quad (3)$$

(2)

The variables chosen to elucidate the problem of linear programming are presented in Figure 1, which exposes the model adopted in the research and the respective inputs (vertical wells, directional wells, field age and Area), intermediate product (volume of oil produced) and outputs (produced water), whose variables were selected from the research developed by Asunção, Vieira & Almeida (2018a , 2018b).

Figure 1 – Production model adopted in the research



The model aims to evaluate the DMU's from an environmental perspective, so the produced water, output of the system, should be minimized in order to reduce the environmental impact of the wells. Since the variable produced water is undesirable, the Multiplicative Inverse (MLT) method developed by Dyson, Allen, Camanho, Podinovski, Sarrico & Shale (2001) was applied in order to transform the undesirable outputs into their inverse. Moreover, the orientation of the DDEA model aims to maximize the inverse function of the produced water.

4. RESULTS AND DISCUSSION

The period under analysis comprised the years between 2014 and 2016. In order to achieve a better fit for the proposed model, the Swallow field was excluded, since it had only two periods of production and high variability. For fields with annual production bellow or equal to 14,841 m^3, the overall average efficiency ranged from 9.43% (Camamú) to 33.47% (Alagoas), as shown in Table 1. The average indices are low, however in accordance with the results derived from the relational model used due to the dynamicity of production (Kao, 2013).

Table 1 - Descriptive by Coastal Basin Group 1

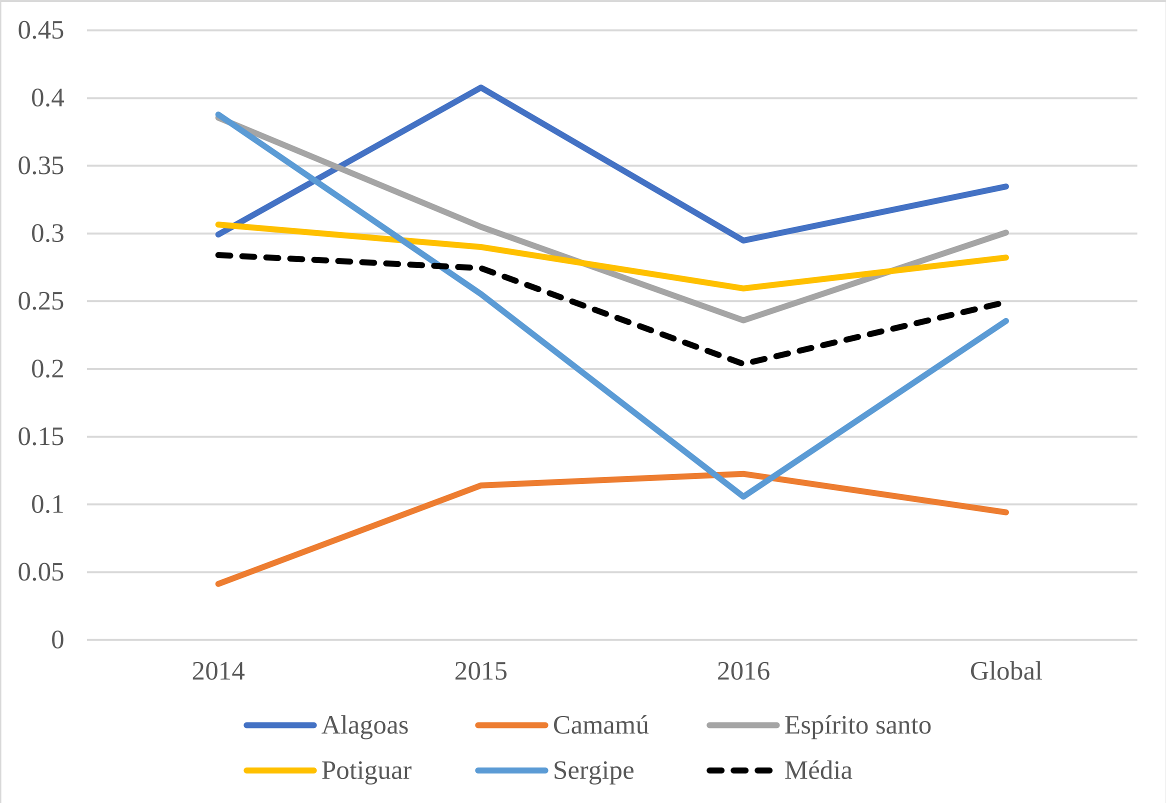
Descriptive	Basins				
	Potiguar	Alagoas	Camamú	Espírito Santo	Sergipe
Average	28,22%	33,47%	9,43%	30,06%	23,54%
Median	22,31%	21,42%	9,43%	25,76%	16,86%
Standard deviation	14,78%	20,95%	7,97%	16,41%	10,79%
Maximum	83,10%	60,76%	17,40%	79,93%	45,57%
Minimum	3,24%	6,25%	1,46%	4,19%	11,30%

Source: Data extracted from Matlab R2014A

It was also observed a high variability of the data confirmed by the discrepant difference between mean and median values for all studied basins, as well as the high standard deviations values, especially in the Alagoas basin (20.95%).

Figure 2 shows the average efficiency for the years analyzed asoociated to all Brazillian onshore coastal basins. When considering the three years analyzed, one can observe a significant decrease in efficiency for the fields loctaed in the Espírito Santo, Sergipe and Potiguar basins. It should be highlighted that, even with the faliure in performance, these basins were above the average of all the studied basins. On the other hand, the Alagoas basin achieved an increase of more than 30% of efficiency in 2015, but presented a sharp drop in the following year, 2016.

Figure 2 – Partial and global efficiencies for Group



Source: Resrach data, 2017.

Table 2 shows the overall and year-on-year efficiency values for the DMU`s of Group 1. One can observe that, on average, the performance in 2014 (33.13%) was higher than the others, with a significant reduction of efficiency in the subsequent years, reaching an index of 23.45% in 2016. This result can be associated to an increase of more than 72% in the number of oil wells, between 2014 and 2016 for the studied fields, increasing the inputs without a proportional reduction in the outputs.

Table 2 – Global and year-on-year efficiencies of oilfields located in the brazilian coastal basin

	Basins	Global efficiency	Efficiency 2014	Efficiency 2015	Efficiency 2016	Injection
Sibite	Potiguar	83,10%	96,10%	58,09%	100,00%	A
Córrego Dourado	Espírito Santo	79,93%	73,22%	100,00%	69,38%	A
Lagoa Bonita	Espírito Santo	72,60%	100,00%	40,06%	79,70%	A
Irerê	Potiguar	66,86%	58,17%	100,00%	41,78%	A
Sabiá	Potiguar	62,56%	0,00%	100,00%	70,87%	A
Sul de Coruripe	Alagoas	60,76%	64,01%	57,40%	60,91%	A
Fazenda Pau Brasil	Alagoas	58,55%	24,06%	100,00%	47,83%	A
Lagoa Piabanha	Espírito Santo	58,17%	71,60%	56,56%	44,45%	A

Trinca Ferro	Potiguar	54,87%	66,96%	44,14%	54,24%	A
Carcará	Potiguar	53,14%	40,15%	24,97%	100,00%	A
Seriema	Espírito Santo	51,19%	56,85%	50,99%	45,49%	A
Biguá	Espírito Santo	48,98%	69,29%	47,23%	27,78%	A
Carapitanga	Sergipe	45,57%	68,01%	30,18%	35,03%	A
Maçarico	Potiguar	39,86%	74,25%	27,07%	25,59%	A
Varginha	Potiguar	39,33%	53,19%	36,50%	26,26%	B
Aruari	Sergipe	39,26%	53,35%	37,26%	25,03%	A
Macau	Potiguar	37,43%	39,61%	38,11%	34,66%	A
Córrego Cedro Norte	Espírito Santo	37,19%	49,00%	31,32%	30,05%	A
Morrinho	Potiguar	36,13%	42,00%	34,17%	31,91%	B
Fazenda Cedro	Espírito Santo	33,87%	52,37%	45,48%	1,77%	B
Rio Mossoró	Potiguar	33,62%	26,92%	29,85%	43,78%	B
Araçari	Potiguar	33,32%	50,92%	30,31%	18,45%	A
Poço Xavier	Potiguar	31,67%	41,59%	41,51%	18,05%	B
Asa Branca	Potiguar	31,53%	38,79%	24,51%	31,67%	B
Fazenda Cedro Norte	Espírito Santo	30,88%	42,93%	27,25%	21,00%	A
Córrego das Pedras	Espírito Santo	26,93%	28,98%	26,97%	24,83%	A
Campo Grande	Espírito Santo	26,76%	38,51%	26,11%	14,18%	A
Fazenda Canaan	Potiguar	26,13%	34,87%	11,95%	33,18%	B
Periquito	Potiguar	25,92%	43,69%	19,72%	13,53%	A
São Mateus Leste	Espírito Santo	25,76%	36,65%	24,97%	16,23%	A
Barrinha Sudoeste	Potiguar	23,59%	40,73%	19,64%	7,55%	A
Guriri	Espírito Santo	21,48%	31,83%	22,35%	9,08%	A
Jequiá	Alagoas	21,42%	21,64%	22,63%	20,00%	A
Iraúna	Potiguar	21,02%	25,75%	22,38%	16,23%	A
Colibri	Potiguar	20,93%	21,70%	21,13%	20,15%	A
Acauã	Potiguar	20,37%	19,19%	18,57%	23,00%	A
São Miguel dos Campos	Alagoas	20,36%	29,02%	18,17%	14,87%	A
Angico	Potiguar	20,25%	23,66%	25,21%	12,30%	A

Ilha Pequena	Sergipe	19,78%	32,55%	26,72%	0,00%	A
Pedra Sentada	Potiguar	19,73%	21,47%	22,61%	15,15%	A
Rio Ipiranga	Espírito Santo	18,93%	24,86%	0,00%	36,18%	A
Barrinha	Potiguar	18,62%	19,05%	20,92%	15,96%	A
Mariricu	Espírito Santo	18,54%	26,60%	14,30%	14,45%	A
Tabuiaiá	Espírito Santo	17,82%	14,91%	27,94%	12,62%	A
Jiribatuba	Camamú	17,40%	7,28%	21,83%	22,11%	A
Juazeiro	Potiguar	17,08%	16,89%	21,49%	13,04%	A
Serra do Mel	Potiguar	16,86%	20,39%	38,54%	12,10%	A
Angelim	Sergipe	16,86%	23,48%	18,45%	8,30%	A
Atalaia Sul	Sergipe	16,69%	42,21%	44,11%	0,00%	A
Riacho Velho	Potiguar	16,51%	0,00%	35,98%	13,92%	A
Mariricu Norte	Espírito Santo	15,91%	29,99%	28,99%	7,87%	A
Tigre	Sergipe	15,32%	27,53%	14,87%	2,29%	A
João de Barro	Potiguar	13,99%	17,44%	14,85%	10,10%	A
Fazenda Junco	Potiguar	13,02%	9,20%	16,92%	12,95%	A
Nativo Oeste	Espírito Santo	11,59%	35,64%	28,17%	0,00%	A
Foz do Vaza-barris	Sergipe	11,30%	24,34%	7,13%	3,36%	A
Crejoá	Espírito Santo	11,08%	11,49%	11,57%	10,32%	A
Gaivota	Espírito Santo	10,98%	0,00%	17,43%	14,84%	A
Rio São Mateus Oeste	Espírito Santo	8,49%	9,11%	7,51%	13,36%	A
Guamaré Sudeste	Potiguar	7,99%	16,70%	6,85%	3,87%	A
Icapuí	Potiguar	6,52%	8,12%	7,54%	4,16%	A
Coqueiro Seco	Alagoas	6,25%	10,94%	5,68%	3,79%	A
Rio São Mateus	Espírito Santo	4,19%	5,66%	5,13%	1,78%	A
Barrinha leste	Potiguar	4,09%	3,22%	6,77%	2,48%	A
Rolinha	Potiguar	3,83%	5,35%	5,54%	1,14%	A
Serra Vermelha	Potiguar	3,24%	4,97%	2,64%	2,17%	A
Morro do Barro	Camamú	1,46%	0,98%	0,97%	2,40%	A
Average		27,30%	33,13%	29,46%	23,45%	

Note: The letter A in the Injection column represents that the field does not use water reinjection as a secondary method of recovery, while the letter B denotes the use of reinjection.

Source: Data extracted from Matlab R2014A.

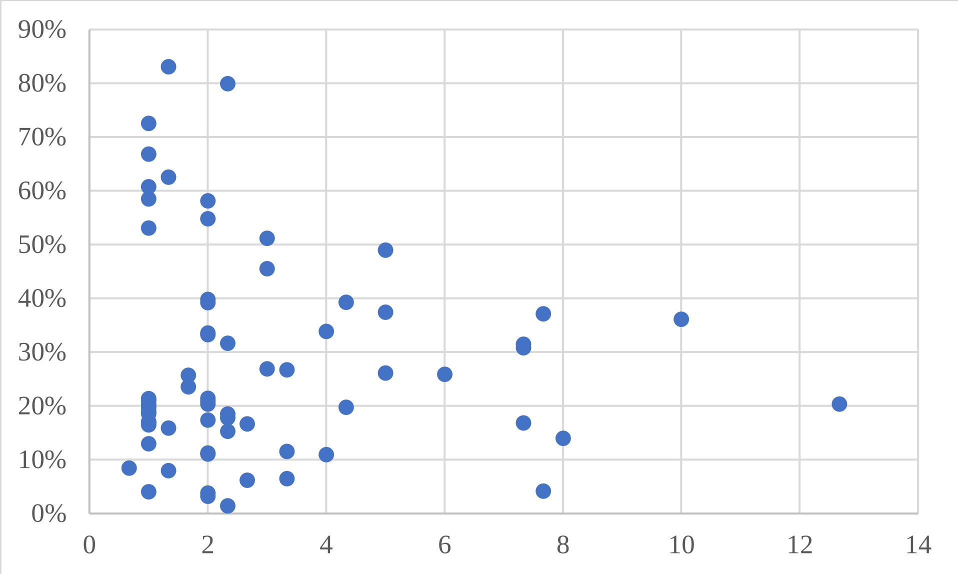
It is important to report that, except the fields Pau Brasil (Alagoas), Maçarico (Potiguar), Sibite (Potiguar), Araçari (Potiguar) and Lagoa Bonita (Espírito Santo) the others have similar efficiency indices in all observed periods. This result provides indications of the need for improvement in processes, aiming to ensure higher levels of efficiency and strategies that do not print a methodological continuity, making it impossible to promote a better management of the produced water from these fields.

It is important to highlight that the two most efficient fields of Group 1, Sibite (Potiguar - 83.10%) and Córrego Dourado (Espírito Santo - 79.93%), are among the three largest producers of this group, although no field has reached the global efficiency frontier. If the annual results were observed, it can be observed that in 2014 only the Lagoa Bonita field reached 100% efficiency. While in 2015, the fields Córrego Dourado (Espírito Santo), Irerê and Sabiá (Potiguar) and Fazenda Pau Brasil (Alagoas) reached the frontier of efficiency. In 2016, only the Carcará and Sibite (Potiguar) fields achieved this result. In addition, the Carcará (Potiguar) field reached the efficiency frontier in 2016, after a 1300% reduction in the volume of produced water, while the Sibite (Potiguar) field achieved a significant decrease in efficiency in 2015 (58.09%), which can be explained by a 32% reduction in oil production and a 28% increase in water production.

Another reality that deserves attention concerns the fields of Lagoa Bonita (Espírito Santo) and Fazenda Pau Brasil (Alagoas). The first obtained a significant decrease in its efficiency index, from 100% to 40.06%, given an increase of 34 times the amount of produced water. The second increased its rate from 24.06% (2014) to 100% in 2015, driven by a 584% increase in oil production. In the following year, Fazenda Pau Brasil (Alagoas) reduced its rate due to the increase in water production and shrinking of oil production.

Figure 3 systematizes the comparison between efficiency per period and the number of wells per field. The values obtained allow to state that fields with the same number of wells have significantly different efficiencies, indicating that the environmental management adopted by each field can positively or negatively influence their performance. It should be noted that the fields that presented the highest efficiencies have one or two wells. These DMU's presented low inputs, justifing the high rates of efficiency obtained.

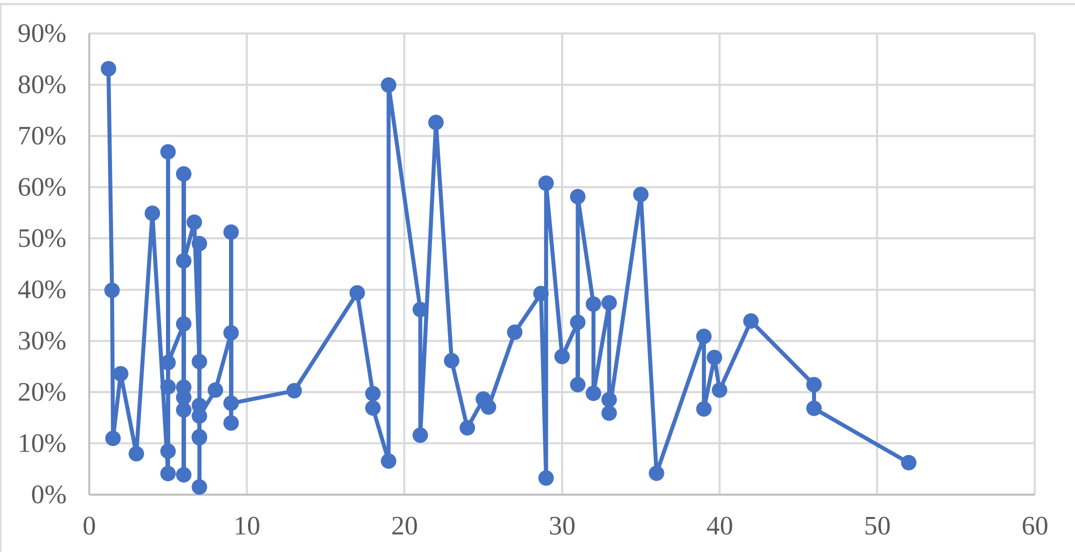
Figure 3 - Comparison between efficiency and number of wells per field Group 1



Source: Research data, 2020.

Figure 4 illustrates the comparison between the age of the field and the measured efficiency. Higher values were observed for the fields at the beginning of production, followed by falls over the second decade of exploration. However, there is a recovery after the twenty years of operation always followed by a downward trend in efficiency. This decline may be related to the effects of increased water production already reported by Khatib & Verbeek (2003); Clark & Veil (2009). These results can be explained by how the output (produced water) is managed over the lifetime of the fields.

Figure 4 - Comparison between efficiency and age of the field Group 1



Source: Research data, 2020.

The authors highlight the good efficiency indexes attributed to the Fields Sibite, Irerê and Sabiá (Potiguar) with production age between 1 and 6 years, to the fields Córrego Dourado and Lagoa Bonita (Espírito Santo) with production time between 19 and 22 years and to the fields Sul de Coruripe and

Fazenda Pau Brasil (Alagoas) with production age between 29 and 35 years. These data suggest that although there is a globaltrend of falling efficiencies, as the production years go by, there are cases in which the managements of the produced water stand out.

Thus, field managers have better know-how regarding the management of this unwanted output with more exploration time, which explains the observed recovery of some of the fields reported in this study.

5. CONCLUSIONS

The proposed model of environmental sustainability for the onshore oil fields of the Brazilian coastal basins highlighted the importance of multidisciplinarity regarding the use of various sciences in order to construct methodologies capable of pointing out/solving latent problems of society.

The relevance of the variables Vertical Wells and Directional Wells for the construction of the dynamic efficiency index was also explained, since their weights had a significantly higher relevance than those adopted for the variables Area and Age.

It was also found that there is a discrepancy in the environmental management practiced by the fields studied, taking into account that the DMU's with similar technological resources presented different productions of produced water and oil, causing inefficiency and unsustainable plants. Inefficiency is the result of unnecessary costs and environmental impacts arising from lack of control and planning of the processes that permeate the oil and gas industry, especially those associated with the reuse and/or disposal of water produced from oil.

Therefore, it can be stated that the management of technological resources, associated with responsible planning, contributes to the volume of produced water for the oil fields of the Brazilian coastal basins. The geometry of the chosen well and the time of exploration are fundamental factors for greater control of the water produced. There is still a large dispersion in the results of similar DMU's, which attests, in general, a mismanagement of resources, especially environmental, resulting in the low rates of overall efficiency measured in this research.

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