Developing an Input-Oriented Data Envelopment Analysis Model for Wastewater Treatment Plants

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Abstract: Although no one can object on the significance of providing high-quality water, the process of wastewater treatment has not been given the same attention, especially in terms of the consideration of the environmental factors. In fact, several tools and techniques have been employed by Wastewater Treatment Plants (WWTPs) for the purpose of improving the efficiency of the treatment process itself. The tool of Data Envelopment Analysis (DEA) can be considered as one of the useful approaches that have been employed in several studies within the context of wastewater treatment. The purpose of this paper is to develop a DEA model for the purpose of measuring the efficiency for a set of WWTPs. Eight different WWTPs located within one of the largest countries in the Middle East were investigated. The proposed DEA model was formulated using four inputs and two outputs. The four Inputs include electricity consumption, number of engineers, number of technicians, and number of workers. The two outputs were the percentage of the removed chemical oxygen demand (COD) and the percentage of the removed suspended solids (SS). Data were analyzed and the results were generated using specialized software for DEA. The results revealed that three out of the eight WWTPs were inefficient. In general, the flexibility of DEA adds a sort of competitive advantage over other tools and techniques.

[Hisham Alidrisi. **Developing an Input-Oriented Data Envelopment Analysis Model for Wastewater Treatment Plants.** *Life Sci J* 2014;11(8):875-879]. (ISSN:1097-8135). http://www.lifesciencesite.com. 130

Keywords: DEA, WWTP, Water Quality, Efficiency.

1. Introduction

Although no one can object on the significance of providing high-quality water (Molinos-Senante et al., 2014), the process of wastewater treatment has not been given the same attention, especially in terms of the consideration of the environmental factors (Lofrano and Brown, 2010). In fact, several tools and techniques have been employed by Wastewater Treatment Plants (WWTPs) for the purpose of improving the efficiency of the treatment process itself. One of the main practical approaches for measuring the efficiency of WWTPs is the benchmarking procedure (Molinos-Senante et al., 2014; Parena et al.; 2002). Molinos-Senante et al. (2014) clarified that the idea of such an approach is to conduct a comparative analysis in order to detect strengths and weaknesses among WWTPs and, consequently, to help in finding ways for cost reduction. Recently, several research works have concentrated on benchmarking procedures (Abbott et al. 2012; Andrews et al. 2011; Quadros et al. 2010).

However, benchmarking methods are not similar. In fact, the easiest one is known as “partial indicators” that considers the ratio of outputs over inputs (Molinos-Senante et al., 2014). This method has been used by Benedetti et al. (2008), Zhao et al. (2010). Though, some important factors have been ignored by these indicators (IBNET, 2012). In this regard, Total Factor Productivity (TFP) is another way of measuring the efficiency. In TFP, an index is developed by determining the ratio of the weighted sum of outputs over the weighted sum of inputs (Molinos-Senante et al., 2014). Marques (2008) calculated the TFP to measure the efficiency of the Water and Sewerage Services (WSS) in Portugal. However, according to IBNET (2012), the benefits of this approach are limited.

Some statistical approaches such as the Ordinary Least Squares (OLS), Corrected Ordinary Least Squares (COLS), and Stochastic Frontier Analysis (SFA) have also been used in this regard (Lin, 2005; Corton and Berg, 2008; and Ferro and Romero, 2011). Recently, Data Envelopment Analysis (DEA) can be considered as one of the useful techniques that have been employed in several studies within the context of wastewater treatment. In this regards, several studies recently applied DEA (Hsiao and Yang, (2007); Sala-Garrido et al., 2012; and Herna´ndez-Sancho et al., 2012). From this point of view, the purpose of this paper is to develop a DEA model for the purpose of measuring the efficiency for a set of WWTPs. Eight different WWTPs located within one of the largest countries in the Middle East were investigated.

2. The Approach of DEA

DEA is a commonly known technique that is applied to assess and improve the operational performance for various processes within many industries. Its recent applications cover many fields such as health care (Guerra and Moreira, 2012), education (Chen and Chen, 2011), banking (Azadeh et al., 2011), manufacturing enterprises (Zhou et al., 2012), energy utilization (Mobtaker et al., 2012), project management (Chang and Lee, 2012), suppliers selection (Kuo and Lin, 2012) and personnel evaluation and selection (Van den Bergh et al., 2012). In this study, the proposed DEA model was formulated using four inputs and two outputs. The four inputs include electricity consumption, number of engineers, number of technicians, and number of workers. The two outputs were the percentage of the removed chemical oxygen demand (COD) and the percentage of the removed suspended solids (SS). COD and SS usually used to measure water quality (Singh et al., 2004). The collected data regarding these inputs and outputs for the investigated WWTPs are summarized in Table1.

Table 1. Inputs and Outputs for the eight WWTPs.

	Inputs				Outputs	
WWTP(i)	Electricity Consumption (in local currency)	Number of Engineers	Number of Technicians	Number of Workers	% Removed BOD	% Removed SS
WWTP 1	3674194.2	5	17	40	98.28	98.98
WWTP 2	1542160	5	17	35	97.72	98.26
WWTP 3	1908123.9	18	20	63	97.78	99.15
WWTP 4	2050580.83	14	62	31	95.89	97.74
WWTP 5	1096738.75	11	45	44	95.96	94.94
WWTP 6	262416.67	5	28	30	96.48	95.36
WWTP 7	897956.33	3	41	27	96.33	94.78
WWTP 8	6314250	2	79	24	93.62	93.22

The First DEA model was developed by Charnes et al. (1978) as follows:

$$Max \quad \frac{\sum_{k=1}^{s} v_k y_{kp}}{\sum_{j=1}^{m} u_j x_{jp}}$$

$$s.t \quad \frac{\sum_{k=1}^{s} v_k y_{ki}}{\sum_{j=1}^{m} u_j x_{ji}} \leq 1$$

$$v_k, u_j \geq 0 \quad \forall k, j \qquad (1)$$

Where for each Decision Making Unit (DMU) under assessment (DMU_p) out of a set of n DMUs (in this case, n $WWTPs$):

There are s outputs,

There are m inputs,

$i = 1, 2, 3, \ldots n.$

$k = 1, 2, 3, \ldots s.$

$j = 1, 2, 3, \ldots m.$

y_{kp} = amount of output k produced by the unit under assessment, $WWTP_p$

y_{ki} = amount of output k produced by $WWTP_i$

x_{jp} = amount of input j utilized by the unit under assessment, $WWTP_p$

x_{ji} = amount of input j utilized by $WWTP_i$

v_k = weight given to output k,

u_j = weight given to input j.

The previous model is called input-oriented DEA multiplier model. Many authors, after that, have developed different DEA models in order to address certain issues within the applications (Charnes et al., 1978; Ali and Seiford, 1993). In this paper, the input-oriented CCR model is employed (CCR refers to Charnes, Cooper, and Rhodes (Charnes et al. (1978)). This model can be expressed as:

$$Min \quad \theta + \varepsilon \left(\sum_{j=1}^{m} s_j^- + \sum_{k=1}^{s} s_k^+ \right)$$

$$s.t. \quad \sum_{i=1}^{n} \lambda_i x_{ji} + s_j^- = \theta x_{jp}, \quad j = 1, 2, 3, \ldots m.$$

$$\sum_{i=1}^{n} \lambda_i y_{ki} - s_k^+ = y_{kp}, \quad k = 1, 2, 3, \ldots s.$$

$$\lambda_i, s_j^-, s_k^+ \geq 0, \quad i = 1, 2, 3, \ldots n. \qquad (2)$$

Where λ_i is the weight given to $WWTP_i$; s_j^- and s_k^+ represent the slack for *input j* and the surplus for *output k*, respectively. Note that ε is an arbitrarily small positive number employed to assure that all of the considered inputs and outputs are not negative. In this situation, technical efficiency for each $WWTP_i$ is achieved if, and only if, both of the following conditions are fulfilled: *1- All slacks = 0; 2- Efficiency score =1.*

3. Results

Data were analyzed and the results were generated using specialized software for DEA, that is, Frontier Analyst 4©. The results revealed that three out of the eight WWTPs were inefficient. Specifically, all WWTPs scored 100% except WWTP 3 (85.7%), WWTP 4 (88.5%), and WWTP 5 (66.8%). Accordingly, potential improvements have been calculated for the three inefficient WWTPs. The results are summarized in Table 2. Figure 1, 2, and 3 presented the potential improvements for WWTP 3, WWTP 4, and WWTP 5, respectively.

Table 2. The Overall Results

		Potential Improvements for Inputs				Outputs	
WWTP(i)	Efficiency Score	Electricity Consumption	Number of Engineers	Number of Technicians	Number of Workers	% Removed BOD	% Removed SS
WWTP 1	100%	0	0	0	0	0	0
WWTP 2	100%	0	0	0	0	0	0
WWTP 3	85.70%	-14%	-71%	-14%	-34%	0	0
WWTP 4	88.50%	-11%	-79%	-21%	-11%	3%	0
WWTP 5	66.80%	-66%	-57%	-33%	-33%	0	0
WWTP 6	100%	0	0	0	0	0	0
WWTP 7	100%	0	0	0	0	0	0
WWTP 8	100%	0	0	0	0	0	0

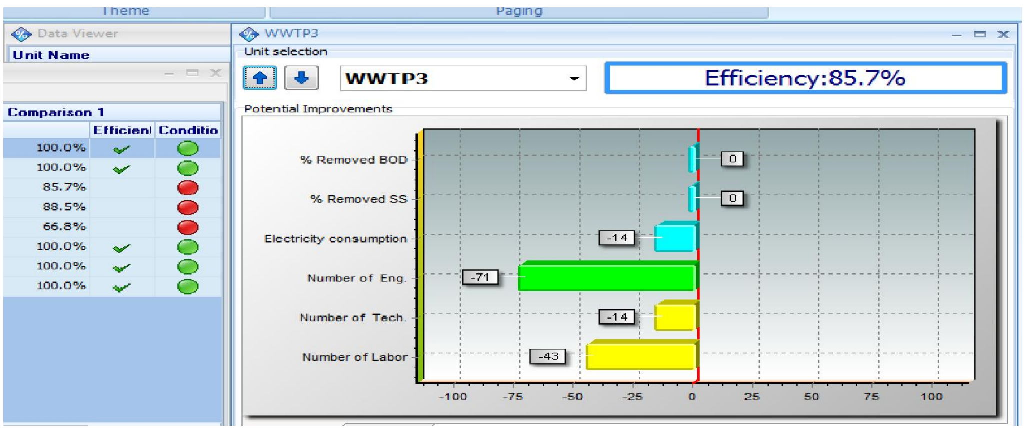

Figure 1. The Potential Improvements for WWTP 3.

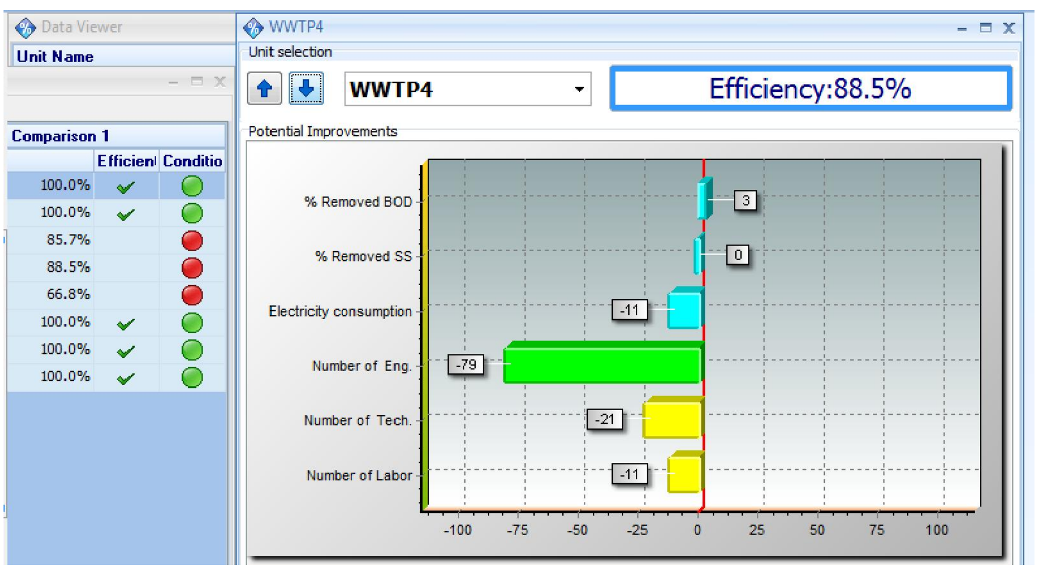

Figure 2. The Potential Improvements for WWTP 4.

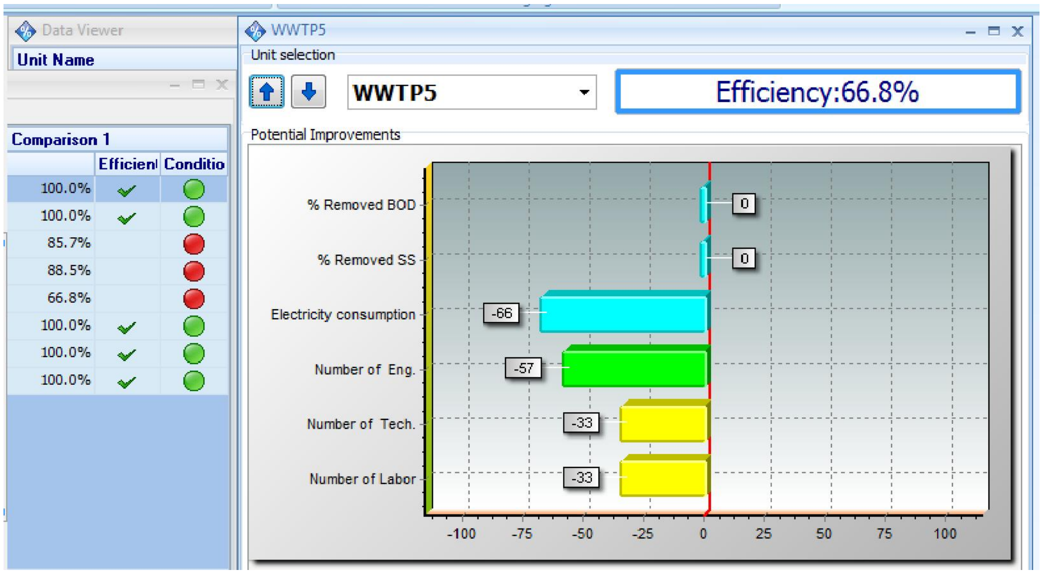

Figure 3. The Potential Improvements for WWTP 5.

4. Discussions

As illustrated in Table 2, in order to improve the efficiency of WWTP 3, electricity consumption, number of engineers, number of technicians, and number of workers are recommended be reduced by 14%, 71%, 14%, and 34% respectively. That means electricity consumption for WWTP 3 should be 1640987 (in local currency) instead of 1908124 (in local currency), number of engineers to be 5 instead of 18, number of technicians to be 17 instead of 20, and number of workers to be 42 instead of 63. Similarly, Regarding WWTP 4, electricity consumption, number of engineers, number of technicians, and number of workers are recommended be reduced by 11%, 79%, 21%, and 11% respectively. That means electricity consumption for WWTP 4 should be 1825017 (in local currency) instead of 2050581(in local currency), number of engineers to be 3 instead of 14, number of technicians to be 49 instead of 62, and number of workers to be 28 instead of 31. Note that for the WWTP 4, the percentage the removed BOD (output 1) is also recommended to be increased by 3% to be 98.77% instead of 95.89%. Finally, in regard to WWTP 5, electricity consumption, number of engineers, number of technicians, and number of workers are recommended be reduced by 66%, 57%, 33%, and 33% respectively. That means electricity consumption for WWTP 5 should be 372891 (in local currency) instead of 1096739 (in local currency), number of engineers to be 5 instead of 11, number of technicians to be 30 instead of 45, and number of workers to be 29 instead of 44.

5. Conclusion

This paper presents DEA as a tool for measuring the efficiency of eight different WWTPs. The proposed DEA model considers four input measures and two output measures. The proposed model is an input-oriented DEA, which in turn directs the potential improvement feedback toward input measures rather than output measures. Indeed, the results reflect such a fact in a sense that almost all inefficient WWTPs have potential improvements in their input measures. However, in some circumstances, the focus might be given to the output measures. Fortunately, DEA can also be formulated in order to obtain potential improvements for output measures; that is the output-oriented DEA model. The selected inputs as well as outputs are also subject to the perception of the decision maker. The number of input and output measures is also subjective. Such flexibility adds a sort of competitive advantage to the DEA approach over other tools and techniques.

Acknowledgements:

The author would like to thank King Abdulaziz University (KAU), Jeddah, Saudi Arabia, for providing the required support in order to conduct and publish this paper. The author also would like to thank Mr. Abdulrahman Mirza for his effort in data collection.

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8/15/2014