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An economic analysis of industrial wastewater treatment systems using multi-attribute decision-making methods (case study: Toos Industrial Estate, Mashhad, Iran)

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ABSTRACT

With the world's remarkably fast industrial development over the recent decades, the strictly controlled treatment of industrial wastewaters and effluents is becoming increasingly essential for preserving our environment. Given the importance of ensuring the compliance of industrial zones with environmental standards, it is indispensable to predict suitable wastewater treatment systems for these zones. Economic analysis of available systems, including the assessment of construction and operating costs, can greatly contribute to the selection of the treatment solution that fits a given area or application. One of the challenges in managing the treatment facilities of industrial estates, similar to the Toos Industrial Estate studied in this paper, is how to upgrade the aerobic treatment units of an existing treatment plant. In this study, the options available for upgrading the aerobic treatment unit of the studied treatment plant are reviewed and the best alternative is chosen by the use of multi-attribute decision-making methods with emphasis on operating cost minimization. The results suggest that using the economically optimum option in the studied plant will result in more than 80% reduction in the operating, energy and maintenance costs of its secondary treatment stage.

Keywords: Economic analysis; Aerobic wastewater treatment; Multi-attribute decision-making; Operating cost

1. Introduction

With the rapid industrial development of the past few decades, the world has witnessed a massive improvement in the variety and availability of consumer products but has also experienced an intensified outpouring of solid wastes, air pollution and industrial wastewater into the environment. In many industrialized countries, production policies are equipped with strict and sophisticated measures put in place with the sole purpose of controlling environmental pollution [1]. It is reasonable to believe that ensuring compliance with environmental laws will strengthen sustainable industries, thereby leading to a sustainable economy [2]. One of the core duties of the management authorities of industrial estates is to design, construct, and manage the industrial wastewater treatment plants that are needed to mitigate the environmental impacts of industrial units operating in their area of responsibility. The shortage of resources that can be dedicated to this cause and the sheer number of industrial estates emerging and expanding across the world both add to the importance of finding cost-effective wastewater treatment solutions. Modeling, simulation, analysis of historical data, and estimation of future costs and trends could provide some insight into how to optimize the cost of wastewater treatment facilities [3]. Naturally, unpredictable factors such as operational problems may complicate cost estimation and economic planning processes, especially in cases that involve aerobic and anaerobic biological techniques [4]. In any case, the sheer size of

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investment and operating costs of treatment plants make it hard to understate the importance of such economic analysis.

In a study by Vouk et al. [5], economic analysis was conducted on wastewater collection and treatment systems using artificial neural networks (ANNs). In this study, ANN was used to estimate the cost of construction, operating, and maintenance of wastewater collection and treatment systems in rural and urban areas [5]. Landry and Boyer [6] conducted a Life Cycle Assessment on urine source separation systems with an emphasis on non-steroidal anti-inflammatory drug removal. In this study, different treatment and separation scenarios were analyzed from two perspectives of environmental impacts and economic costs [6]. In another study, Li et al. [7] compared the available options for the improvement of wastewater collection and management systems for two particular cases, a hospital and an apartment complex with more than 100 residential units, by conducting an economic analysis with emphasis on charge saving strategies. In a research by Elazzouzi et al. [8] on the potential use of electro-coagulation/flocculation for cost-effective removal of pollutants, they investigated whether this method can be used for the effective and economic removal of chemical oxygen demand (COD), biochemical oxygen demand during the 5-day (BOD_5), total suspended solid (TSS), nitrate (NO_3), nitrogen (N), phosphorus (P), and fecal coliform (FC) [8]. Gisi et al. [9] studied the use of inexpensive adsorbents in wastewater treatment. In this study, they compared the treatment potentials of five groups of adsorbents: agricultural and household wastes, industrial by-products, sludge, sea materials, soil and ore materials, and novel low-cost adsorbents. The aim of this research was to remove pollutants such as phosphate, nitrogen, and bio-recalcitrant compounds, heavy metals, and various types of dye [9]. Djukic et al. [10] conducted a cost-benefit and cost-reflective tariff analysis for a wastewater treatment project in Serbia. In this study, economic analyses were performed using the methodologies recommended by the European Commission [10].

In a study by Eggimann et al. [11], the cost of on-site wastewater treatment and its relation with the area density were analyzed using soft computing techniques and specifically heuristic algorithms. In this study, transportation was considered to be the central component of investment and operating costs. The comparisons of this study were mostly based on centralized wastewater management systems and decentralized wastewater management systems [11]. Cui et al. [12] investigated the cost-effective options for improving dye removal efficiency in the operation of bio-electrochemical systems. In this study, a cost-effectiveness analysis was conducted on two methods, wastewater dilution or mixing of glucose or acetate with the influent [12]. The present study aims to estimate the investment and operating costs of several industrial wastewater treatment plants using computer simulation, and then determine the most cost-effective alternative among the available options with the help of different decision support systems.

2. Materials and methods

This study aimed to perform an economic analysis on various methods of biological treatment of industrial wastewaters. In industrial wastewater treatment systems, anaerobic reactors alone cannot reduce the organic load to standard levels and but a combination of aerobic and anaerobic reactors are needed for this purpose. This research was conducted in the format of a case study on the wastewater treatment plant of the Toos Industrial Estate, Mashhad, Iran. The biological process of this treatment plant is a combination of upflow anaerobic sludge blanket (UASB) and anaerobic attach growth and suspended growth systems. The first phase of the study involved the simulation of these methods in CapdetWorks 2.5, comparison with other options, and an economic analysis. In the second phase, several multi-attribute decision-making (MADM) methods were used to determine which treatment systems are more cost-effective for this particular treatment plant and similar projects in other industrial estates.

2.1. Case study

Toos Industrial Estate is a 360-hectare industrial estate located 15 km northwest of Mashhad, in Khorasan-Razavi Province, Iran. This industrial estate consists of three phases and first became operational in 1992. At the time of this study, 440 out of 615 industrial units projected in the first and second phases were operational and the rest were under construction or in financing stages, and thus were excluded from the study. The estate's treatment plant has two influents with the TSS, total dissolved solid (TDS), COD, and annual flow specifications given in Figs. 1–4, respectively (all figures are for 2015).

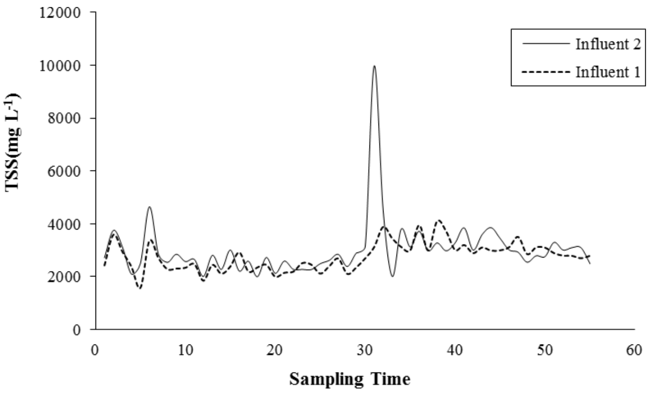

Fig. 1. TSS of influents 1 and 2 of the Toos industrial wastewater treatment plant.

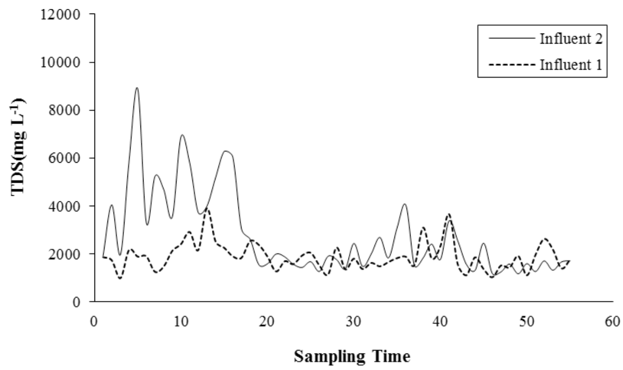

Fig. 2. TDS of influents 1 and 2 of the Toos industrial wastewater treatment plant.

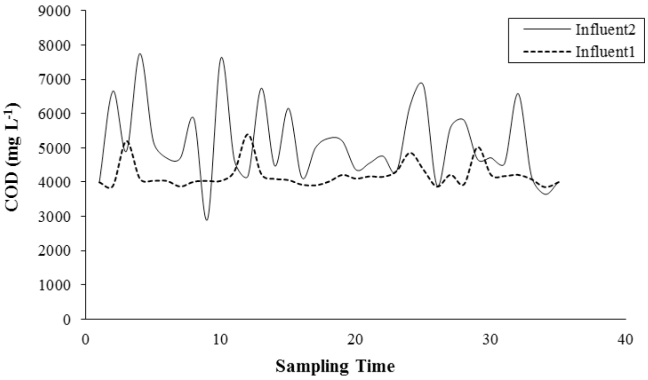

Fig. 3. COD of influents 1 and 2 of the Toos industrial wastewater treatment plant.

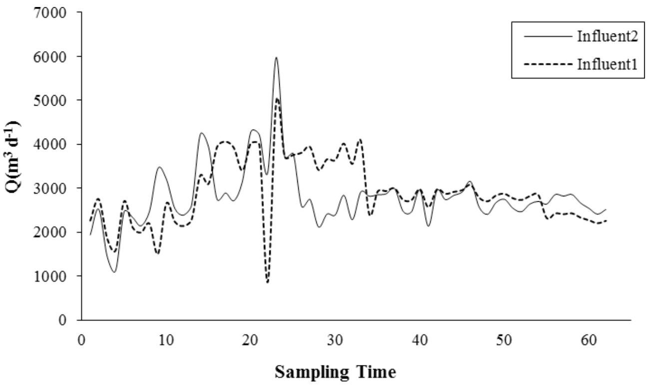

Fig. 4. Input flows of the Toos industrial wastewater treatment plant.

In this section, the aerobic treatment methods are compared first with each other and then with other methods and then subjected to an economic analysis. The models discussed as follows are assumed to consist of identical preliminary treatment, primary clarification, equalization, ion exchange, UASB process, chlorination, gravity thickening, aerobic digestion, belt-filter press, hauling and landfilling processes and only differ in terms of the method of aerobic biological treatment or chemical treatment (coagulation and flocculation).

2.2. Economic simulation

CapdetWorks is a software tool for economic analysis and preliminary design of industrial wastewater treatment systems. This software has been developed for cost analysis purposes. The economic processing algorithm of this software operates based on the solid retention time (SRT), influent fractionation, and activated sludge model. CapdetWorks has been developed based on the recommendations of Activated Sludge Model No. 1 (ASM1), Metcalf & Eddy (Waste Water Engineering: Treatment & Reuse, 4th edition) [13], and Theory, Design and Operation of Biological Nutrient Removal Activated Sludge by the Water Research Commission. In the present work, eight treatment scenarios including both biological and chemical systems were defined (Table 1). The costs of each scenario, including operating cost, energy cost, cost of chemical agents and other consumables, and maintenance cost were then evaluated.

Table 1
Industrial wastewater treatment scenarios for economic comparisons

Scenario ID	Changed component
1	Sequence batch reactor (SBR)
2	Oxidation ditch (OD)
3	Completely mixed reactor (CMR)
4	Trickling filter (TF)
5	Aerated lagoon (AL)
6	Extended aeration (EA)
7	Rotating biological contactor (RBC)
8	Coagulation and flocculation (Coag.)

2.3. MADM methods

MADM is a systematic process for selecting the best option from among multiple predefined alternatives according to a number of predefined criteria or measures. MADM consists of four basic phases: identification and evaluation, weighting, selection, and sensitivity analysis [14]. In general, the relative weight of criteria can be estimated in three ways: using objective data, using subjective data (priorities and preferences of the decision maker), and using a combination of both [15,16]. In this study, the entropy technique is used for this purpose.

2.3.1. Entropy technique

In the context of information theory, entropy is the amount of uncertainty expected in the contents of a given piece of information. In other words, entropy is a metric for measuring uncertainty in a discrete probability distribution such as P_i, where there is more uncertainty involved when the distribution is broader. This uncertainty can be expressed by Eq. (1) [17] as follows:

$$E_J = -k\sum_{i=1}^{m}\left[p_{ij}.\ln p_{ij}\right],\ \forall_{ij} \tag{1}$$

In this equation, P_{ij} is the decision matrix made from the normalized data. After obtaining $d_j = 1 - E_j$, the weight of each measure (W_j) can be calculated using Eq. (2). If the decision-maker has a subjective preference about the relative importance of measures (λ_j), then the abovementioned equation transforms into Eq. (3).

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}, \quad d_j = 1 - E_j, \quad \forall_j \tag{2}$$

$$w_j^{'} = \frac{\lambda_j.w_j}{\sum_{j=1}^{n}\lambda_j.w_j}\ ; \quad \forall_j \tag{3}$$

There are a variety of MADM methods for choosing the best option from among a set of alternatives. In this study, this was done using the analytic network process (ANP), elimination and choice translating reality (ELECTRE), technique for order preference by similarity to ideal solution (TOPSIS) and hybrid weighted averaging (HWA) and the results were compared. Given the uncertainty involved in different phases of the MADM process, it is crucial to conduct a sensitivity analysis to estimate the risk-aversion of the chosen method and the decision-makers.

2.3.2. TOPSIS

Originally introduced in 1981 by Hwang and Yoon [18], TOPSIS is a decision support method operating based on the idea that the best choice among a set of alternative solutions is the one that is most similar to the ideal choice (ideal but impossible) and least similar to the worst choice, also known as anti-ideal. In TOPSIS, this idea has been translated into a search for the solution with the least distance from the ideal solution and the most distance from the anti-ideal solution. Note that TOPSIS is applicable only when values and relative weights of criteria can be expressed as deterministic numbers [19]. In this method, the first step is to normalize the decision matrix. Having this matrix, the weight vector expressing the relative weight of criteria should be used to obtain the weighted normalized decision matrix as follows:

$$V = N_D \cdot W_{n*n} \tag{4}$$

In this equation, W is the diagonal weight matrix, where only the entries on the main diagonal are nonzero, N_D is the decision matrix, and V is the weighted normalized matrix [20]. The next step is to determine the ideal and anti-ideal solutions:

$$\begin{cases} J = \{ j = 1,2,...,n \mid j \in \text{BENEFIT}.\} \\ J' = \{ j = 1,2,...,n \mid j \in \text{COST}.\} \end{cases}$$
$$\begin{aligned} A^+ &= \{ (\max V_{ij} \mid j \in J), (\min V_{ij} \mid j \in J') \mid i = 1,2,...,m \} \\ &= \{ V_1^+, V_2^+, ..., V_n^+ \} \\ A^- &= \{ (\min V_{ij} \mid j \in J), (\max V_{ij} \mid j \in J') \mid i = 1,2,...,m \} \\ &= \{ V_1^-, V_2^-, ..., V_n^- \} \end{aligned} \tag{5}$$

The distance of each alternative (A_i) from the ideal solution (d_i^+) and from the anti-ideal solution (d_i^-), and the closeness coefficient (cl_i^+) of that alternative must then be calculated using the following equations:

$$\begin{aligned} d_i^+ &= \left\{ \sum_{i=1}^{n} (v_{ij} - v_j^+)^2 \right\}^{0.5}; \; i = 1,2,...,n, \\ d_i^- &= \left\{ \sum_{i=1}^{n} (v_{ij} - v_j^-)^2 \right\}^{0.5}; \; i = 1,2,...,n, \\ cl_i^+ &= \frac{d_i^-}{d_i^- + d_i^+} \end{aligned} \tag{6}$$

Naturally, the closer the alternative to the ideal solution, the closer the cl_i^+ value will be to the unity.

2.3.3. ELECTRE

This approach involves rating the solutions based on a concept called outranking [17,20]. For instance, in this approach, $A_k \to A_l$ means the decision-maker or risk analyst believes that solution A_k is preferable over solution A_l. The first step of this method is to normalize the decision matrix using Eq. (7) as follows:

$$n_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{n} r_{ij}^2}} \tag{7}$$

Having the normalized decision matrix, the weighted normalized matrix should be calculated using Eq. (4). Next, Eq. (8) should be used to obtain the harmonic set (S_{kl}) and the anharmonic set (D_{kl}) and Eq. (9) should be used to calculate the harmonic coefficient I_{kl}:

$$D_{kl} = \{ j \mid r_{kj} < r_{lj} \}; \qquad S_{kl} = \{ j \mid r_{kj} \ge r_{lj} \} \tag{8}$$

$$I_{kl} = \sum_{J \in S_{KL}} w_j; \qquad \sum_{j=1}^{n} w_j = 1 \tag{9}$$

Note that, the value of I_{kl} represents how important A_k is compared with A_l. Next, the anharmonic matrix should be calculated using Eq. (10):

$$NI_{kl} = \frac{\max_{j \in D_{KL}} \left| V_{kj} - V_{lj} \right|}{\max_{j \in J} \left| V_{kj} - V_{lj} \right|} \tag{10}$$

The effective harmonic matrix must then be obtained based on a veto threshold using Boolean matrices F and G:

$$\begin{aligned} &\bar{I} = \sum_{k=1}^{m} \sum_{l=1}^{m} I_{k,l} / m(m-1) && \overline{NI} = \sum_{k=1}^{m} \sum_{l=1}^{m} NI_{k,l} / m(m-1) \\ &\text{if}: I_{k,l} \ge \bar{I} \to f_{k,l} = 1 && \text{if}: NI_{k,l} \ge \overline{NI} \to g_{k,l} = 1 \\ &\text{if}: I_{k,l} < \bar{I} \to f_{k,l} = 0 && \text{if}: NI_{k,l} < \overline{NI} \to g_{k,l} = 0 \end{aligned} \tag{11}$$

In the end, the matrix h representing the relative preference of solutions is obtained using Eq. (12):

$$h_{k,l} = f_{k,l} \cdot g_{k,l} \tag{12}$$

2.3.4. Analytic network process

ANP is a generalization of analytic hierarchy process (AHP), which is not restricted by the strictly hierarchical structure of AHP, and hence is better-equipped for analyzing more complex decision problems [21]. ANP is able to model the interdependence of the elements of a phenomenon or problem as a multi-layer or multi-rank decision network. While not being as popular as AHP, ANP has found increasing application in many areas of decision making.

2.3.5. Hybrid weighted averaging

Introduced by Xu and Da [22], HWA is an averaging operator that takes into account not only the importance of variables but also their order. The HWA operator has been defined as follows:

$$\mathrm{HWA}_{v,w}(a_1,a_2,\ldots,a_n)=\sum_{j=1}^{n} v_j b_j \tag{13}$$

where v_j is the weight vector of the operator and $\sum_{j=1}^{n} v_j = 1$. This weight vector v_j is obtained in the same way as in the OWA method. The parameter b_j is the j-th largest value in the set of descendingly ordered alternatives $nw_i a_i$. The vector $W = (w_1, w_2,\ldots, w_n)^T$ represents the weights of alternatives a_i ($i = 1, 2,\ldots, n$) and $\sum_{j=1}^{n} w_j = 1$, ($j = 1, 2,\ldots, n$). Here, the parameter n acts as a balancing coefficient. Assuming that the decision maker is evaluating s alternatives with respect to n criteria, the HWA operator gives the final value of each alternative as follows:

$$r_i = \mathrm{HWA}_{v,w}(r_{i1},r_{i2},\ldots,r_{\mathrm{in}}), \quad i=1,2,\ldots,s \quad j=1,2,\ldots,n \tag{14}$$

where r_{ij} is the decision maker's assessment of alternative i according to criteria j and w_j (j = 1, 2,… n) is the vector of relative weight of criteria in these assessments, for which we have $w_j \geq 0$ and $\sum_{j=1}^{n} w_j = 1$. Here, $v = (v_1,\ldots,v_t)^T$ is the weight vector of the HWA operator. In this study, the weight vector of the HWA operator was obtained using the linguistic quantifiers proposed by Yager [23]:

$$w_i = Q\left(\frac{i}{n}\right) - Q\left(\frac{i-1}{n}\right), \quad i=1,2,\ldots,n \tag{15}$$

where i is a counter, n is the total number of criteria, and Q is a linguistic quantifier. The membership function is a linguistic quantifier that reflects the concept of fuzzy majority and is used in the calculation of weight vector for the aggregation operator. The quantifier function Q can be obtained using the strictly monotonic relation $Q(r) = r^{\alpha}$, which has extensive use in the calculation of quantifier membership function. It should be noted that the function Q is closely related to the extent of optimism, which can be estimated using Eq. (16):

$$\text{Orness }(w) = \int_0^1 Q(r)dr = \int_0^1 r^{\alpha}dr = \frac{1}{\alpha+1} \tag{16}$$

In this equation, Orness is the optimism degree and α is the optimism factor. If $\alpha > 1$, then orness(w) < 0.5 indicating that the decision-maker is pessimist or risk-averse, if $\alpha = 1$, then orness(w) = 0.5 indicating that the decision maker is risk-neutral, and if the $\alpha < 1$, then orness(w) > 0.5, indicating that the decision maker is optimist or risk-taker [24]. In this work, α value was determined using the definition proposed by Zarghami et al. [25]. The optimism and quantifier parameters and their linguistic equivalents in this definition are given in Table 2.

3. Results and discussion

As mentioned earlier in the paper, the first phase of the study was to simulate the wastewater treatment plant of the Toos Industrial Estate in CapdetWorks 2.5. Using the simulation, the annual costs of operating, maintenance, materials, energy, depreciation, and chemical agents in eight scenarios of Table 1 were estimated. The estimated costs for these scenarios are illustrated in Fig. 5.

As shown in Fig. 5, the sequence batch reactor (SBR) system has the highest operating cost among the considered options. This method requires at least two tanks, one for the filling stage and another for the reaction, settlement and discharge stages. Moreover, this method involves subjecting the installations to a recurring loading/unloading cycle, which leads to increased maintenance and depreciation costs [26]. This method also involves keeping the installations continuously on-line (hydraulic retention time is 18–30 h) and has the second highest energy consumption after the EA system [27]. It should also be noted that because of its

Table 2
Parameters of monotonically ascending optimism [25]

Linguistic quantifier	Optimism factor (α)	Optimism degree (θ)
At least one of them	0 (α = 0.01)	0.99
Few of them	0.1	0.9
Some of them	0.5	0.7
Half of them	1	0.5
Many of them	2	0.3
Most of them	10	0.1
All of them	100	0.01

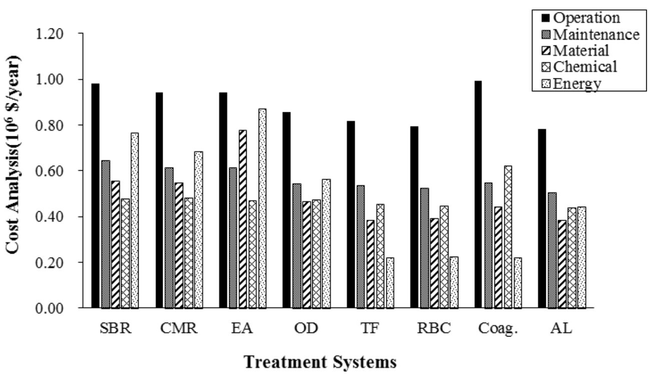

Fig. 5. Economic analysis of operating cost, maintenance cost, material cost, energy cost, and cost of chemical agents in eight scenarios considered for the wastewater treatment plant of the Toos Industrial Estate.

complexity and sensitivity, this method is more susceptible to upsets, which may impose significant recovery costs on the operator [28]. In the EA method, the system operates in the self-digestion phase, so reactors should have a low organic loading and long aeration. This method has an SRT of 20–30 d and an HRT of 24 h, which indicates that aeration is governed by mixing and not oxygenating [29]. Therefore, aerators are continuously online, which results in very high energy consumption [30]. Since energy cost is one of the major cost factors of treatment systems, this has led to a significant difference between the cost of this method and all other methods except SBR (Fig. 5).

Note that the SBR, completely mixed reactor (CMR), and EA methods also have the highest annual depreciation cost as they involve keeping the more expensive installations online. In the CMR method, it is important to maintain the uniform distribution of organic load, MLSS concentration, and the oxygen demand over the aeration pond [31]. This means that surface or submersible aerators of the reactor must constantly remain online, and this significantly increases the energy consumption. This method also has a higher maintenance cost than the aerated lagoon (AL), rotating biological contactor (RBC), oxidation ditch (OD), and trickling filter (TF) methods because of the continuous operation of aerators and mixers (if present). The OD method consumes far more energy than the AL, RBC and TF methods, because it involves equipping a circular or oval channel with mechanical and aeration equipment to keep the wastewater circulating at a certain speed to maintain the desired suspension, while diluting the mixture by 20–30 times as the cycle is repeated [32]. In the AL method, the factor that raises the operating cost is the energy consumption of the equipment tasked with aeration, mixing, and bringing oxygen to microorganisms [33]. It should be noted that because of the large surface of reactors in the AL systems, this method requires consuming large amounts of chemicals to adjust alkalinity, pH, nutrient supplementation, etc. [34].

Overall, the AL, RBC, OD, and TF methods have very close chemical costs (to adjust the alkalinity, pH, nutrient supplementation, or other settings of the operation), material costs, and maintenance costs and the only factor that significantly affects their operating cost is the aeration process. Hence, the aeration process can be regarded as the bottleneck of cost optimization. In the TF method, the attached growth process leads to a reduced need for aeration and consequently greatly reduced energy consumption, which sharply decreases the operating cost [35]. In the RBC method, also, the rotation of the attached growth surfaces facilitates aeration and oxygenation of microorganisms, thereby reducing the energy consumption and the consequent operating cost [36].

In Figs. 6 and 7, the initial investment cost and the depreciation cost obtained from simulations are presented. Note that this study was conducted under the assumption of no restriction on the investment cost and with focus on the operating costs to be incurred over a 40-year period (project lifespan). The reason behind this assumption is that in the studied case, the project owner has acquired a suitable plot of land at a very low price and dedicated it to water treatment purposes. Also, planning, control, and initial financing of the treatment project, including the investment needed for construction, are not within the area of responsibility of

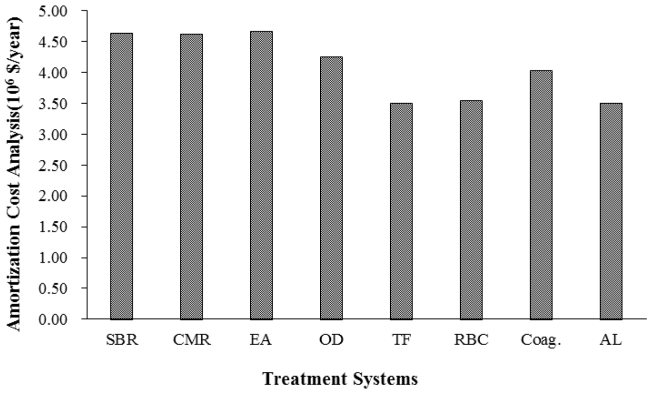

Fig. 6. Economic analysis of depreciation cost in the eight scenarios considered for the studied case.

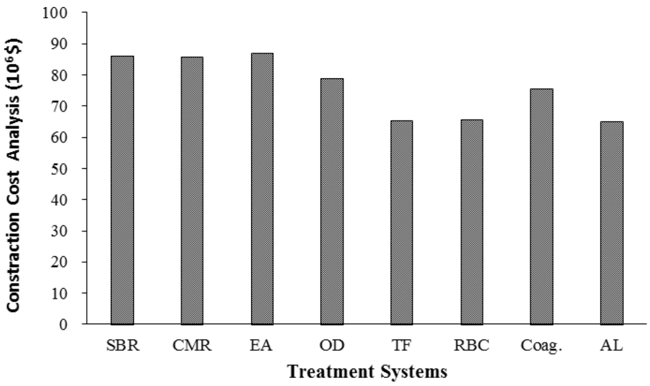

Fig. 7. Economic analysis of land and construction cost in the eight scenarios considered for the studied case.

the project owner (Toos Industrial Estate Company) and are guaranteed to be handled by the supervising government organizations.

In an economic study of treatment facilities by McGivney and Kawamura [37], the investment cost was considered to be separate from the construction cost, and they were analyzed from two different perspectives. Following this approach, the present study chose to focus the economic analysis on the operating costs [37]. In another study, Gratziou and Chrisochoidou [38] estimated the costs of wastewater treatment plants with the help of statistical methods and analyses. This study presented Eq. (17) for predicting the operating, energy, and construction costs of wastewater treatment plants [38]. It should be noted that Gratziou and Chrisochoidou's study was performed in Greece and his estimations were based on the conditions of that region.

$$\text{Cost}_i = a + bQ - cQ^2 \tag{17}$$

In the abovementioned equation, *a*, *b*, and *c* are the coefficients of operating, energy, and construction costs. Having an approximation of the input flow of the studied treatment plant, energy, and operating costs were estimated using Eq. (17). As shown in Tables 3 and 4, the results of Gratziou function are not consistent with the results of CapdetWorks.

This discrepancy can be attributed to the difference between the base energy and labor costs of Greece and Iran. Also, Gratziou's model operates exclusively based on the input flow and this overdependence may cause an error in its estimations.

Before making any decision regarding the most economical choice for the studied case, the evaluation criteria were studied and ranked using the Shannon entropy method. In these evaluations, which were performed with the help of Osborn's brainstorming technique, the weights of operating, maintenance, material, energy, chemical, and depreciation costs were calculated to 0.21, 0.12, 0.24, 0.15, 0.18, and 0.09, respectively. As explained earlier in the paper, this study aimed to choose the most economic treatment solution for the wastewater of the Toos Industrial Estate using four MADM methods (ANP, ELECTRE, TOPSIS, and HWA).

As shown in Fig. 8, all MADM methods recognized the EA and SBR methods as the least economical choices for the project in question. For the HWA method, the analysis was performed at all levels of optimism defined in Table 2. Even after configuring the HWA to produce the most optimistic output, this method found that EA and SBR are the least economic choices among the considered methods. In Iran, energy pricing policies are not aimed at reducing energy loss or making better use of renewable energies. As a result, the price of energy in Iran is far lower than its actual value. Hence, to make a more realistic decision, in the entropy method, the energy criterion was given a lower weight than it would have been given if it had its real value (i.e., something resembling its global value). In other words, if we had considered the true value of energy, the EA method would have had even more clear disadvantage compared with other methods in terms of operating cost. In a comparative study of secondary treatment methods by Gratziou et al. [39], they reported that the EA method is the most expensive and the OD method is the most economical choice among these methods [39].

Table 3
Annual energy cost estimations obtained from CapdetWorks and Gratziou function (10^2)

Aerobic treatment system	CapdetWorks model	Statistical model of Gratziou and Chrisochoidou [38]
CMR	455	71.77
OD	340	60.136

Table 4
Annual operating cost estimations obtained from CapdetWorks and Gratziou function (10^2)

Aerobic treatment system	CapdetWorks model	Statistical model of Gratziou and Chrisochoidou [38]
CMR	102	230.5
OD	27.4	197.68

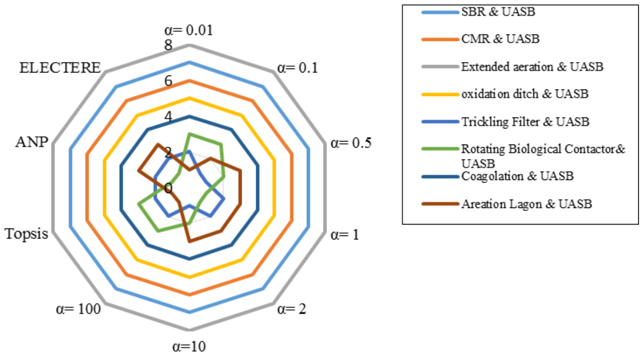

Fig. 8. Results of the MADM methods regarding the choice of the most economical wastewater treatment method for the Toos Industrial Estate.

The results of ANP, ELECTERE, TOPSIS, and HWA in all optimism levels indicate that the Coag., RBC, AL, and TF are the top four economical choices for the case studied. Because of the inefficiency of chemical sludge approach, potential environmental impacts of the leakage of chemicals, and many other technical, operational, and environmental reasons cited in references, among these four methods, the biological method could be considered a better candidate. From the analyses of decision-making methods, it was deduced that the RBC method is the best economical choice. After considering the overall design of the treatment plant and comparing the units to be involved, it was found that, in terms of operating cost, the anaerobic sludge stabilization and the UASB treatment system with the annual operating costs of, respectively, $237,000 and $173,000 are the most expensive units. In terms of energy cost, the anaerobic sludge stabilization unit, the belt filter press, and the equalizer with the annual costs of, respectively, $87,500, $63,200, and $34,200 are the first to third most expensive units in this respect. Regarding the sludge dewatering, Gratziou et al. have reported that the belt filtration is 10%–35% more efficient than the belt filter press [39].

One of the most important aspects of economic management is the supervision over maintenance costs. The highest maintenance costs estimated for the studied case were related to the anaerobic stabilization unit with an annual maintenance cost of $132,000, the anionic and cationic exchange units each with an annual maintenance cost of $108,000, and the UASB system with an annual maintenance cost of $68,000. In a study by Chougule and Sonaje, a cost-benefit analysis of textile wastewater treatment plants showed that ion exchange treatment costs about $0.01384 per L of textile wastewater treated [40]. As shown in Fig. 9, the operating, energy, and maintenance costs of the aerobic treatment unit in the RBC system are, respectively, $3,200, $14,000, and $6,900 per year. But in the EA system, these costs are, respectively, $119,000, $649,000, and $70,500 per year. This means using the EA system instead of the RBC system will reduce the annual operating, energy, and maintenance costs of the aerobic treatment by 97.3%, 97.8%, and 90.2%, respectively. At present, the studied plant is equipped with a CMR system, for which the annual operating, energy, and maintenance costs were estimated to be $941,000, $682,000, and $615,000, respectively. It should be noted that all of the abovementioned costs have been estimated based on international standards.

In Fig. 10, the depreciation costs of different units of the treatment plant are compared with each other. These results show that the annual depreciation of the RBC unit is only $80,500, but that of the EA and SBR methods are $966,000 and $389,000, respectively.

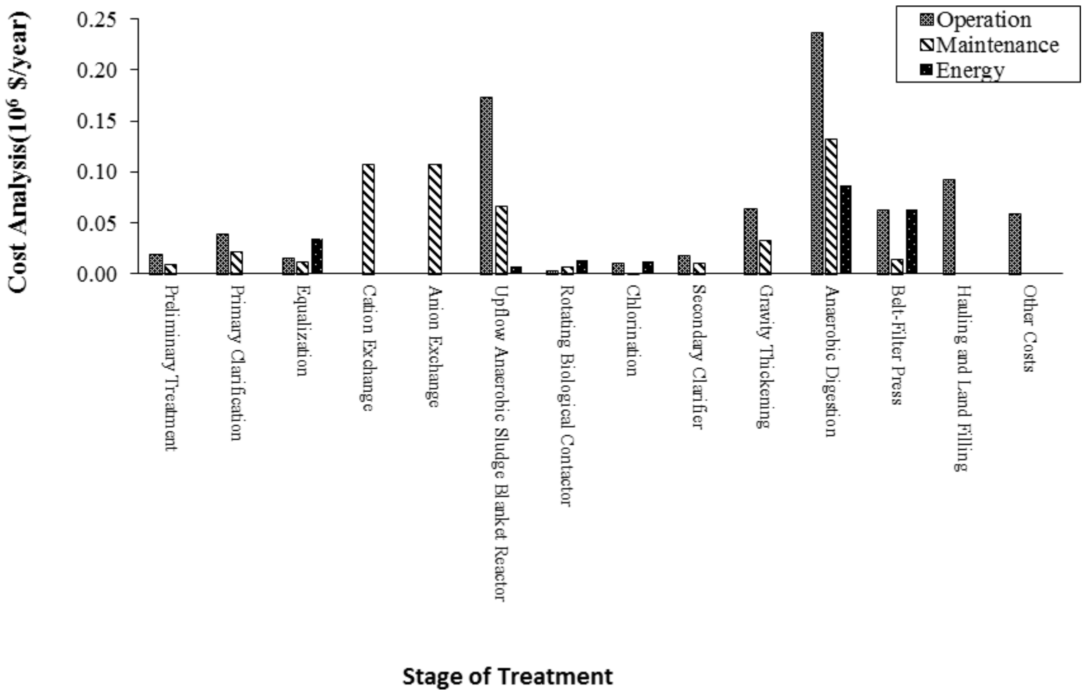

Fig. 9. Operating, energy, and maintenance costs of different units in the studied case.

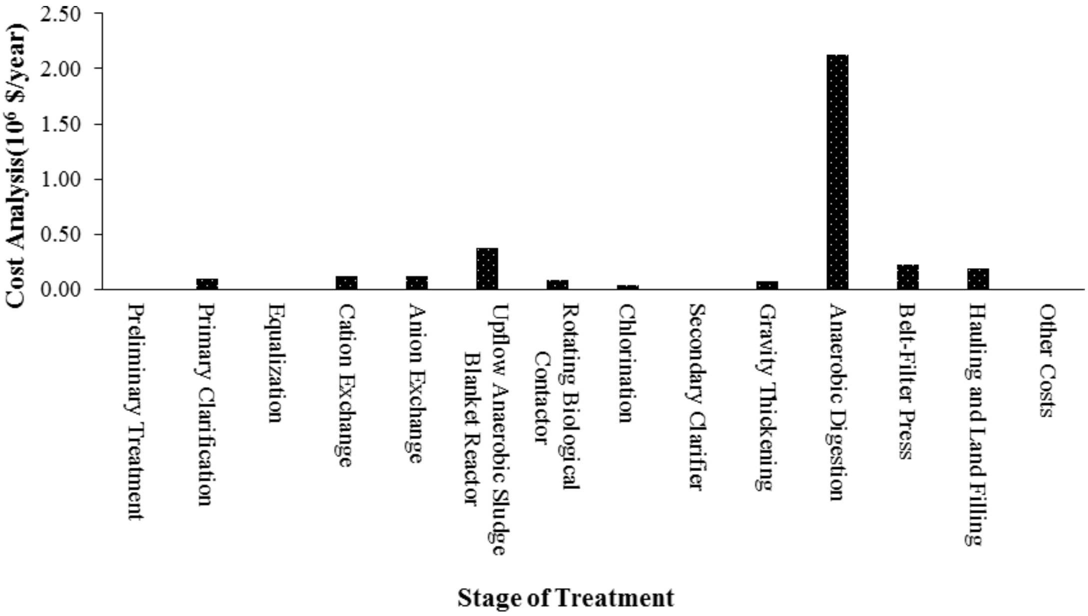

Fig. 10. Depreciation cost of different units in the studied case.

The simulation results showed that the ratio of the total sum of operating, energy, and maintenance costs of the UASB system to that of the RBC was 10.7, but the same ratio for the EA, SBR, and CMR systems was 0.3, 0.31, and 0.42, respectively. This indicates that the EA, SBR, and CMR systems are more economically consistent with methods such as UASB than are the RBC, AL, and TF systems. Given the organic load of industrial wastewaters, their treatment has to include high-efficiency anaerobic processes [41]. The past experiences of using the UASB have demonstrated its ability to reduce the COD and BOD_5 loads to an acceptable level. Nevertheless, these anaerobic systems cannot reduce the organic load to a level that would be acceptable for recipient water resources. Hence, to get a standard outflow in terms of COD, BOD_5, and organics concentration, anaerobic and aerobic systems should be combined together. Indeed, one of the goals of the simulation conducted in this study was to find out which serial combination of anaerobic and aerobic methods in question could be sufficiently economical to be considered for this purpose.

4. Conclusion

The success or failure of a project in achieving its long-term goals depend on how thorough it has been studied and whether all factors that influence its performance have been duly considered in the decision-making and project management processes. One of the major concerns in the management of industrial estates is the choice of the systems to be used in the wastewater treatment plant. In this study, the efficiency and applicability of several MADM methods in choosing the most economical wastewater treatment system for an industrial estate were investigated in the format of a case study on the Toos Industrial Estate located near Mashhad (Iran). For this purpose, four MADM methods, namely ANP, ELECTRE, TOPSIS, and HWA were used to choose the best alternative among available options according to different criteria, and the results were compared with each other. The results obtained in different scenarios and from the sensitivity analysis of the results showed the advantage of biological methods and that overall the RBC method is the best economical choice for this particular case. The results indicate that the HWA method, which is capable of incorporating into the selection process not only the importance weight of selection measures but also the decision maker's degree of optimism and risk-aversion, can serve as an excellent support tool for decision making and analysis in the area of industrial wastewater treatment. After comparing the CMR system currently deployed in the Toos Industrial Estate with the choice extracted from the economic analysis, that is, the RBC system, it was found that using the RBC system instead of CMR will reduce the annual operating, energy, and maintenance costs of aerobic treatment by 99.65%, 97.95%, and 98.88%, respectively, and will reduce the initial investment cost by 23.54%. Hence, it is highly recommended to conduct more thorough studies on the prospects of developing the studied plant and certainly take more caution before constructing other treatment plants with similar conditions.

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