# A Novel Fuzzy Framework for Technology Selection of Sustainable Wastewater Treatment Plants based on TODIM Methodology in Developing Urban Areas

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**A Novel Fuzzy Framework for Technology Selection of Sustainable Wastewater Treatment Plants based on TODIM Methodology in Developing Urban Areas**


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**Abstract**

Optimum technology selection of wastewater treatments plants (WWTPs) necessitates the adoption of data-driven scientific approaches that satisfy the sustainability requirements of the urban ecosystem. Such approaches should be able to provide actionable insights to decision makers constrained by factors such as increasing population, scarcity of land, and loss of functionality of treatment plants. In this article, we present a criteria system based on the sustainability perspective, which is crucial for the selection of the treatment plant technology from the planning to the operation of the plants. We further suggest a hybrid fuzzy multi-criteria decision making framework (MCDM) under the concept of the alpha cut series which takes into account the risk aversion of decision makers to overcome uncertainties of environmental conditions. To the best of our knowledge, this study is the first to show how a systematic decision-making process is approached by interpreting the interaction of criteria for the selection of treatment plant technology through the membership function of Prospect Theory. The prominent reference criterion manages other sub-criteria according to the function of risk-aversion behavior. The alternatives are ranked by the fuzzy TODIM (an acronym in Portuguese of interactive and multi-criteria decision-making) based on α-cuts sets integrated into the fuzzy analytical hierarchy process (FAHP) including the aggregated weights. We verify usefulness of our approach through a case study conducted with four full-scale WWTPs in a metropolitan city of an EMEA country. The ranking results based on dominance degree of alternatives showed that anaerobic-anoxic-oxic (A2O) without pre-clarification was the most effective process according to sludge disposal cost (C25) calculated as reference criteria. Finally, we present how our framework can be utilized by reflecting the risk perception of decision makers in technology selection of WWTPs for developing urban areas.

*Keywords:* Wastewater treatment plant, Technology selection, Sustainable Development, Multi-criteria decision making, Fuzzy TODIM, Prospect Theory, Fuzzy Analytical Hierarchy Process, Sustainable Development

## Introduction

Economic development should be balanced with protection of natural resources and environmental sustainability to contribute to the circular economy. Wastewater is defined as a valuable resource for both ecological and economic development of countries in terms of sustainability[1]. Wastewater treatment makes a major contribution to sustainable development in terms of water resources protection, effective waste management, and openness to the use of renewable energy[2]. Increasing the proportion of safe and most appropriate technologies for treating domestic and industrial wastewater is considered one of the expanded goals of the Sustainable Development Goals (SDG) by 2030[3].

Optimum technology selection for the wastewater treatment process can only be achieved by ensuring the right investment for the right region, taking into account public benefit and social awareness. In real life, the optimal technology selection for wastewater treatment plants depends directly on the knowledge, experience and competence of the decision makers[4]. Uncertainties related to forecasts of economic, social, and environmental conditions can have manipulative effects on stakeholders' attitudes (e.g., risk aversion or risk-taking in making decisions) and lead to limitations in rational decision-making that requires sufficient knowledge of prevailing conditions[5]. For this reason, the motivation of this study is to overcome the limitations of the unpredictability of human behavior caused by uncertainty by reflecting the risk-aversion perspectives of competent decision-makers in a proposed decision-making model for selecting the most appropriate technology for wastewater treatment plants (WWTPs).

Wastewater treatment technology selection is a complex and multidimensional problem necessitating multi criteria evaluation[6]. In addition to the complexity of the problem, decision makers are faced with the necessity of evaluating contradictory criteria which, seems to be another challenge in the problem[7]. Accordingly, much research has been done to assess this interaction between economic or technological feasibility and environmental impacts in order to select the optimal wastewater treatment alternative over the lifetime of treatment systems. Among them, Molinos-Senante et al.[8,9] propose a systematic approach based on the analytic hierarchy process AHP and scenario-based analytic network theory (ANP) to address the assessment of economic feasibility and environmental impact in the decision-making process for ranking alternatives. In recent years, most studies on the economic assessment and environmental impacts of alternatives to wastewater management, including wastewater treatment plants, have been conducted by applying a multi-criteria decision-making approach (MCDM) that focused on expert opinion[10]. Furthermore, some of these studies should be conducted with exact data as opposed to heterogeneous data, however, this is not always possible with real-world problems. All these mentioned studies contribute with different perspectives to cope with the complexity of the decision-making process for the technology selection of wastewater treatment plants and uncertainties from dynamic environments.

In this article, we focus on the impact of behavioral psychology on decision-making process, considering the possibility of reference dependency, loss-averse, and subjective judgement bias to select the optimum technology for WWTPs under risks and uncertain environments. One of the reference studies in behavioral economics is the Prospect Theory developed by Kahneman and Tversky in 1979[11], a descriptive model that includes behavioral expectations for individual decisions under risk conditions. Prospect theory treats changing individual behavior under risk and uncertainty as a description of reference-dependent losses and gains. Although the effect of behavioral psychology on decision-making processes is repeatedly emphasized in the literature on wastewater management, it describes it qualitatively in decision-making models. On the other hand, it is possible to use this mechanism in quantitative decision models via prospect theory to make more rational decisions. In this context, Autran Monteiro Gomes and Duncan Rangel in 2009[12] introduced an MCDM method based on prospect theory and considering psychological behaviors under risk and uncertainty, known as the TODIM method (an acronym in Portuguese for interactive and multi-criteria decision-making) is abbreviated. Q. Qin et al. in 2017[13] introduced a TODIM-based approach to behavioral decision making integrated with an intuitionistic fuzzy set to transform linguistic data for business model selection related to energy efficiency. Guo et al. in 2020[14] improved an extended TODIM methodology using a hesitant fuzzy set to select carbon capture, utilization and storage technologies to represent ambiguity in decision making.

Starting from this perspective, we introduce a fuzzy multi-criteria decision framework based on Prospect Theory to integrate bounded rational human behaviors, emphasized by many studies in behavioral economics to decision model for WWTP selection problem. In contrast to traditional decision-making tools, the methodology proposed in this study is worth showing the results of reference-dependent decisions that reflect loss-averse behavior and ranking the alternatives according to their degree of dominance by showing the criteria interaction. Additionally, the criteria system is established including all sustainability dimensions that allow comprehensively analyze not only single effect of specific environmental impact such as greenhouse gas effect or treated water reuse but rather the whole operations from the construction to operation. The diverging aspect of this study from the other studies on wastewater management is that in the decision making process, sustainability indicators determine the dominance degree of the technologies used in real-scale WWTPs in accordance with the membership function of the Prospect Theory. The strongest aspect of this framework is that it enables more rational decisions by determining the crucial criteria that influence the concept of sustainability under variable and uncertain conditions according to the risk aversion approach. On the basis of this perspective, the results we have reached according to the proposed decision model which considers the behavioral characteristics of decision makers reveal the strong interaction between economic and environmental criteria in real scale decision problems for WWTPs, and also provide reducing distortion of subjective judgements or information loss. In this study, the reference dependency approach reflects the decision model based on the loss avoidance behavior of decision makers and our results show that the sludge disposal cost calculated by our decision model as ‘’reference criterion’’, which is sub criteria of economic dimension of sustainability, interact strongly with sludge generation, operational and maintenance cost, and energy savings for determination of the dominance degree of each alternatives. According to the calculated dominance degree of alternatives, A2O (anaerobic-anoxic-oxic) without pre-clarification was the most effective process in terms of sustainability perspective. All these findings indicate that while the model simulates the reference dependency of human behavior with a focus on risk aversion, the weight of the criteria that will affect the reference criterion weight is also effective in the alternative ranking.

When the contributions and limitations of researches on decision-making processes on the environmental policies are examined, the following inferences seems to emerge:

(1) Necessities of multi-dimensional evaluation of the problem by establishing criteria system,
(2) Achieving the evaluation of heterogeneous types of information such as linguistic, interval or crisp data and demonstration of the criteria interaction
(3) Dealing with uncertainty arising from dynamic environmental conditions and human prejudices,
(4) Reflecting the behavioral psychology of decision makers in the decision process quantitatively,
(5) Managing the decision process by overcoming incomplete, corrupted or insufficient data.

Based on these inferences, we introduce a fuzzy TODIM based approach from sustainability perspective by criteria evaluation, dealing with heterogeneous types of information and reflecting risk avoidance behavior of decision makers considering dynamic environmental conditions. To the best of our knowledge, this is the first study to integrate all aspects of sustainability with the behavioral characteristics of decision makers such as reference dependence, loss avoidance, risk seeking. Following our approach, when an emergency decision making is required such as sudden change in population, limitations of land and energy, fuzzy TODIM model can offer a more scientific framework for the ranking of alternatives.

The contributions of this study can be summarized as: (1) a fuzzy TODIM method based on α-cuts set performed by trapezoidal fuzzy numbers is proposed which provides reliable way to reveal criteria interaction in dynamic environment by changing qualitative and quantitative data into fuzzy information contrary to traditional approaches. (2) The proposed methodology presents a rational approach unlike traditional methodology to select optimum technology for WWTPs reflecting risk averse behavior of decision makers into decision model. (3) This fuzzy approach based decision model reduces loss of information and eliminate distorted data to make decision closer to the real case by the strength of membership function of Prospect Theory.

## Material and Methods

### Study Area and Evaluation of Alternatives

Istanbul is Turkey's most populous metropolitan city with a population of over 15 million residents, settled on an area of 5.34 $km^2$. Being a mega city, Istanbul forms the highest population density in Europe. Due to the fact that it receives a large in-migration, in recent years population growth was recorded as almost twice as expected. Istanbul faced problems in terms of water availability throughout its history, but the situation has worsened with the rapid population growth over the last decade[15]. Wastewater in Turkey, which has not been valued until recently, is nowadays being considered as a possible '*new*' source of clean water to be used especially for non-potable purposes. Due to this reason, technology selection for wastewater treatment process needs to be evaluated to serve not only to meet discharge limits, but also the other aspects related with sustainability such as reuse of treated wastewater and protection of water resources. In Turkey, ecological issues related sustainability including treated wastewater reuse, energy efficiency, and renewable energy usage in WWTP, green house effects, and sludge treatment techniques are not always taken into consideration at the same time rationally. Our case study in Istanbul involves four types of technologies applied for four WWTPs with a capacity of more than 100.000 $m^3$/ day. In this research, the alternatives are collected under four different process titles namely, Conventional Activated Sludge System with pre-clarification and digester (CAS-W/-P) (A1), A2O without pre-clarification (A2O-W/O-P) (A2), 5-stage Bardenpho with pre- clarification (BP-5-W/-P) (A3) and finally, A2O with pre-clarification (A2O-W/-P) (A4).

### Methodology

Our study comprise four major parts, in the first part, a hierarchical criteria system for WWT technology selection problem is established, and major criteria and sub-criteria is explained. In the second part, data transformation and normalization is performed using TrFNs. Followed by, criteria and sub-criteria weights are evaluated by AHP. In addition, aggregate criteria weights of both quantitative and qualitative data are calculated by deriving them from the methodology developed by Abdel-Kader and Dugdale in 2001[16]. In the final part, alternatives of WWT technologies are ranked according to fuzzy TODIM method based on α-cuts set adapting the value function of prospect theory. We performed our model development using MATLAB software and data transformation and normalization and sensitivity analysis in relation to the changing attenuation factor ($\theta$) and comparative study using method in the literature.

### Establishment of Criteria System based on sustainability dimensions

Wastewater treatment activities are considered high-priced and effort-driven due to land requirement, complex processes, and energy cost[17]. Due to this reason, criteria evaluation is considered to be a strategic part of decision making problems considering sustainability[18]. In this study, the dimensions of sustainability were selected based on the following four major criteria: Environmental, economic, technical and social aspects. In order to propose a decision model with criteria evaluation based on scientific foundations, questionnaire study was conducted with experts involved in every stage from the feasibility to construction and operation of WWTPs. Furthermore, environmental impact assessment reports, specifications including design parameters for WWTPs, regulations regarding treated water discharge parameters, and literature were investigated to build a criteria system. Finally, we determined 24 sub-criteria grouped under the main aspects of sustainability based on relevant literature and research group meetings to build criteria system considering the complex process of wastewater treatment as presented in Fig. 1. The definition and explanation of these sub-criteria are shown in Table 1.

Environmental factor includes the impacts of wastewater treatment activities that affect ecosystem and resources. Considering the environmental impacts, resource consumption and reusability concepts, three criteria were determined to evaluate the environmental efficiency of WWTPs: energy consumption, sludge production, and reuse of treated water.

Economic factor is a measure of the extent of expenses from the installation phase of plant to operation phase that the system operate without interruption including investment cost, operation and maintenance cost and land requirement[19]. Cost-oriented and eco-friendly designs of WWTPs is important for decision makers in maintaining the balance between compliance with environmental regulations and budget constraints[20]. For this reason, there are five economic indicators including investment cost, land requirement, operational and maintenance cost, energy savings, and sludge disposal cost were used to evaluate economic viability of the WWTPs.

Technical factor indicates the treatment efficiency, performance, and technological validation of WWTP to achieve desired goals dictated by legislation[21]. The technical criteria directly relate to efficiency of treatment process including removal efficiency of biological oxygen demand (BOD), chemical oxygen demand (COD), suspended solid (SS), nitrogen (N) and phosphorus (P) to perform advanced biological treatment. These sub-criteria show the performance of treatment and the fulfillment of design commitment of WWTP. The efficiency is calculated as follows:

$$\text{Efficiency} = \frac{\text{Influent-effluent}}{\text{Influent}} \text{ x } 100 \text{ (\% BOD, COD, SS, N, and P )}$$

Moreover, six more criteria were added to measure technical performance, which are maturity, simplicity, applicability, replicability, flexibility, and reliability.

Social factor associates with awareness, cultural acceptance, responsibility, and the staffing components of sustainable development that measures the socio-economic value added to overall benefit of wastewater treatment facilities[22].

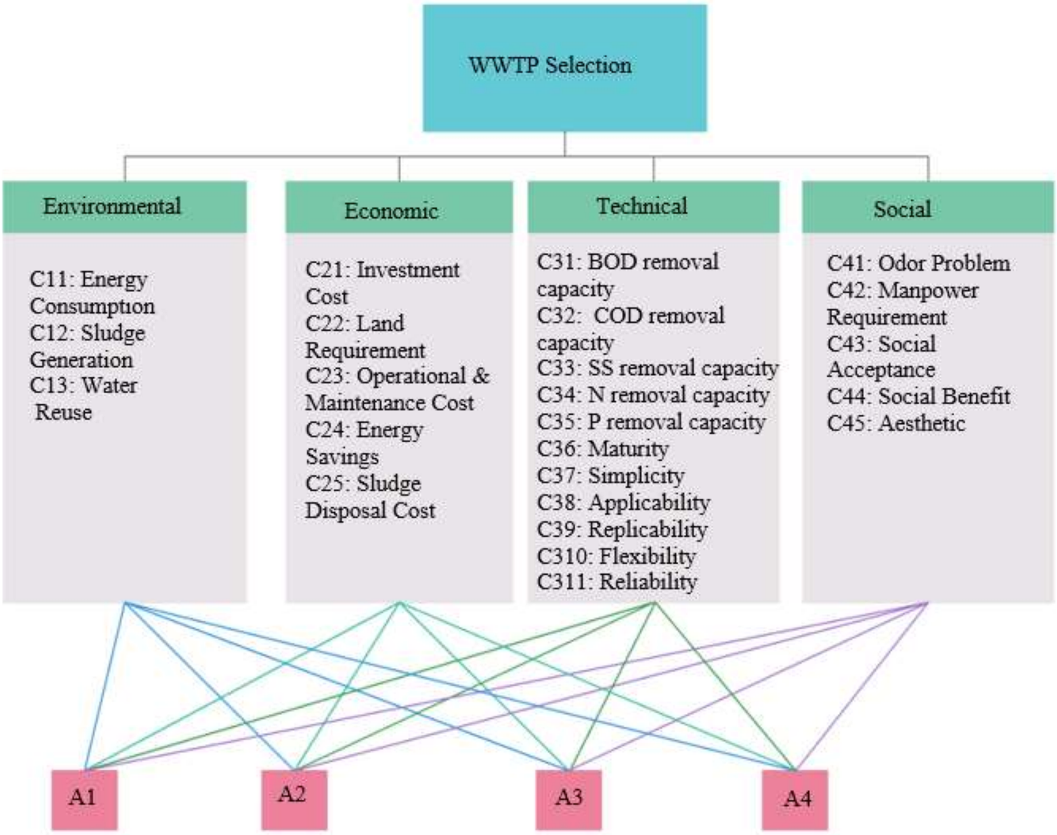


**Figure 1.** Establishment of criteria system for WWTP selection

| Criterion | Explanation |
|---|---|
| *C1: Environmental Criteria* | |
| C11: Energy Consumption | Energy consumption amount during operation to assess carbon footprint, greenhouse gas effect and carbon emissions |
| C12: Sludge Generation | Sludge production of the system |
| C13: Water Reuse | The usage potential of water after treatment |
| *C2: Economic Criteria* | |
| C21: Investment Cost | Expenses for the construction of the wastewater treatment plant |
| C22: Land Requirement | Sufficient space for wastewater treatment plant/ future expansion |
| C23: Operational & Maintenance Cost | Repair, personnel, chemical and energy costs to manage wastewater treatment plant |
| C24: Energy Savings | Energy recovery to reduce total energy costs of the system |
| C25: Sludge Disposal Cost | Expenses of sludge treatment; Sludge Disposal Cost = unit cost of sludge disposal × sludge generation (kg/year) |
| *C3: Technical Criteria* | |
| C31: BOD removal capacity | The removal capacity of the amount of oxygen consumed by microorganisms while decomposing organic matter |
| C32: COD removal capacity | The removal capacity of the amount of oxygen consumed to oxidize all organic material by chemical oxidants |
| C33: SS removal capacity | The removal capacity of the amount of tiny solid particles that act as a colloid |
| C34: N removal capacity | Nitrogen removal capacity |
| C35: P removal capacity | Phosphorus removal capacity |
| C36: Maturity | Applicability of the system |
| C37: Simplicity | Ease of installation, less operation and maintenance and technical staff requirement, availability of on-line plant tracking |
| C38: Applicability/ Operability | Applicable of the system for changing climatic and geographic conditions and population |
| C39: Replicability | Adoptability to any location under the same conditions to allow practical selection for DMs. |
| C310: Flexibility | Sensitive to changing organic load, hydraulic load, allow process changes |
| C311: Reliability | Includes plant performance, equipment reliability and emergency operations |
| *C4: Social Criteria* | |
| C41: Odor Problem | Undesired smell potential of the system |
| C42: Employment | Employment creation of the system |
| C43: Social Acceptance | Public awareness |
| C44: Social Benefit | Added-value of local community to aware environmental issues |
| C45: Aesthetic | Acceptability of plant conditions and appearance |



**Table 1.** Evaluation Criteria for WWTP selection

The procedure to determine subjective judgements of each criteria by using AHP are as follows[23]:

i) The pairwise comparison matrix A is established and standardized.

ii) Each column element of the subjective judgements matrix, $a_{jk}$ is normalized according to equation as follows and called normalized pairwise comparison matrix N

$$\bar{a}_{jk} = \frac{a_{jk}}{\sum_{i=1}^{n} a_{jk}}, \quad i = 1,2, \dots, n \text{ and } j = 1,2, \dots, m \tag{1}$$

where $\bar{a}_{jk}$ is the element of N.

iii) The relative weights of criteria or criteria weight vector are obtained by the row average of normalized matrix N. Eigen vector, $\bar{w}_j$ is calculated to represent criteria weight vector and expressed as follows.

$$w_j = \sum_{k=1}^{n} a_{jk} \tag{2}$$

$$\bar{w}_j = \frac{w_j}{\sum_{i=1}^{n} w_j} \tag{3}$$

iv) Final step is calculation of the consistency index (CI) to measure consistency of experts' judgements according to Eq.(4)

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

where $\lambda_{max}$ is the maximum eigenvalue, n is the rank of the pairwise comparison matrix and $CI < 0.1$ is acceptable for the consistency of the pairwise matrix.

Criteria weights obtained by AHP are demonstrated in Fig. 2. According to the scores, economic factors (C2) are of primary importance and the effect of sludge disposal cost (C25) as a sub-criterion seems higher than other economic indicators. In order to make a weighting that can cope with the uncertainty arising from subjective judgments or inaccurate data in decision problems containing qualitative and quantitative data, the criterion weights to be included in the decision model were determined by using TrFNs at the second phase of this study.

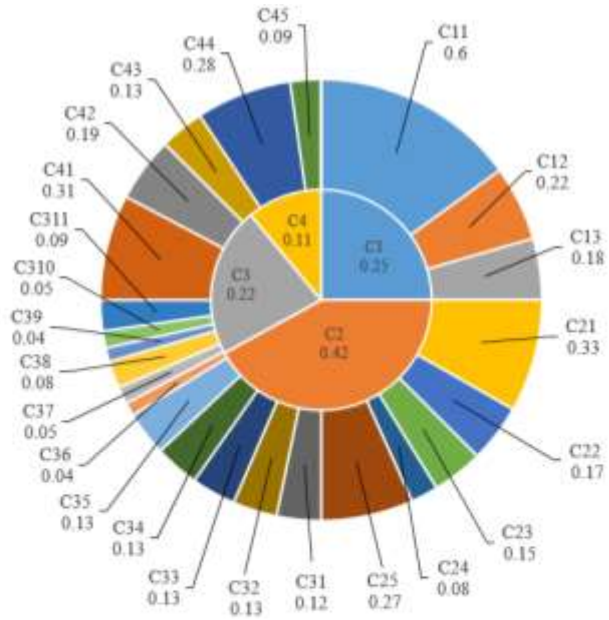


**Figure 2.** Weights of criteria and sub-criteria

**Preliminaries of Trapezoidal Fuzzy Numbers**

Simplification of a fuzzy number is achieved effectively by the piecewise linear curves leading to triangle, trapezoidal, or orthogonal membership function[24]. In this study TrFN is used to model fuzzy data for the reason of the effectiveness of TrFN to solve MCDM problems where the lack of knowledge, and ambiguity nature of human decision making process consists[25]. On the other hand, there exists studies suggesting that TrFN is suitable to modelling imprecision and reflecting the ambiguous nature of subjective judgments[26,27].

**Definition 1.** A TrFN $\tilde{a}$ is a special fuzzy subset on the real number set represented as $\tilde{a} = (a_1, a_2, a_3, a_4)$ whose membership function is as follows[24].

$$\mu_{\tilde{a}}(x) = \begin{cases} 0, & x < a_1 \\ \frac{X - a_1}{a_2 - a_1}, & a_2 \geq x \geq a_1 \\ 1, & a_3 \geq x \geq a_2 \\ \frac{X - a_3}{a_3 - a_4}, & a_4 \geq x \geq a_3 \\ 0, & x > a_4 \end{cases} \tag{5}$$

where the $a_1$ and $a_4$ are lower and upper limits of $\tilde{a}$ respectively and $[a_2, a_3]$ is a closed interval.

**Definition 2.** Widely used standard method for defuzzification is the centroid method. S $(\tilde{a})$ represents defuzzified value of a trapezoidal fuzzy number calculated as follows [28]:

$$S(\tilde{a}) = \frac{a_1 + a_2 + a_3 + a_4}{4} \tag{6}$$

**Definition 3.** Let $\tilde{a}$ and $\tilde{b}$ be two trapezoidal fuzzy numbers such that, $\tilde{a} = (a_1, a_2, a_3, a_4)$ and $\tilde{b} = (b_1, b_2, b_3, b_4)$. Then Euclidean distance $d(\tilde{a}, \tilde{b})$ between two TrFNs is calculated as[29]:

$$d(\tilde{a}, \tilde{b}) = \sqrt{\frac{1}{6}\left[\sum_{i=1}^{4}(b_i - a_i)^2 + \sum_{i \in \{1,3\}}(b_i - a_i)(b_{i+1} - a_{i+1})\right]} \tag{7}$$

**α-Cuts in TrFNs Sets**

The α-cut sets are the way of comparing or ranking the fuzzy numbers without membership functions[30].

**Definition 4.** Let $\tilde{A}$ fuzzy number and its α-cuts $\tilde{A}_\alpha$ are defined as[31]

$$\begin{aligned} \tilde{A}_\alpha &= \{x \in X \mid \mu_{\tilde{A}}(x) \geq \alpha \\ &= [min\{x \in X \mid \mu_{\tilde{A}}(x) \geq \alpha\}, \max\{x \in X \mid \mu_{\tilde{A}}(x) \geq \alpha\}] \\ &= [(x)_\alpha^L, (x)_\alpha^U]. \end{aligned} \tag{8}$$

where $\mu_{\tilde{A}}(x)$ is the membership function of $\tilde{A}$ , $x \in X$ denotes the elements belonging to the universal set and $\forall \alpha \in [0,1]$. Each α-cut set consists of closed intervals containing the upper and lower bound values derived from the fuzzy numbers. According to Definition 4, TrFNs are expressed at α-cuts as follows [32].

$\tilde{A} = (a_1, a_2, a_3, a_4)$ is a TrFN and its α-cut set can be denoted as

$$\tilde{A}_\alpha = [\tilde{A}^L_\alpha, \tilde{A}^U_\alpha] = [a_1 + \alpha(a_2 - a_{1)}, \ a_4 - \alpha(a_{4-} a_3)] \tag{9}$$

**Prospect Theory**

The major concept of prospect theory developed by Kahneman and Tversky in 1979[11] is that decision making depends on behavioral tendency under risks considering the potential value losses and gains representing variability with respect to reference point selection. The value function of prospect theory is described as follows.

$$\mu(z) = \begin{cases} z^\alpha & if\ z \geq 0 \\ -\lambda(-z)^\beta & if\ z < 0, \end{cases} \tag{10}$$

where z denotes gains or losses; $z \geq 0$ represents the gains and $z < 0$ represents losses, and α is the risk seeking coefficient and β is the risk averse coefficient. The expression λ is called the risk aversion coefficient and $\lambda > 1$ represents that decision maker is more sensitive to losses than gains. The value function of Prospect Theory is an s-shaped (sigmoidal) function, consisting of concave and convex part representing gains and losses respectively. In summary, decision makers are risk averse for gains and risk-seeking for losses [33].

Kahneman and Tversky in 1979[11] defined α, β and λ in their empirical research and determined their values as $\alpha = \beta = 0.88$ and, λ =2.25.

**The TODIM Method**

The TODIM Method is attributed as a hybrid method combining aspect of MAUT (Multiattribute Utility Theory) of AHP and ELECTRE methods[12]. In general, MCDM problems have a set of finite number of alternatives: $A = \{A_1, \dots, A_m\}$ and a set of finite number of criteria: $C = \{C_1, \dots, C_n\}$. The weighting vector of criteria $W = \{w_1, \dots, w_n\}$ and the individual weight $w_k$; $k = \{1, \dots, n\}$ for each criterion $C_k$ satisfying $\sum_{k=1}^{n} w_k = 1$. Let $D = (x_{ik})_{mxn}$ be a normalized decision matrix $x_{ik}$ denoting the assessment or performance of alternative $A_i$ related to criterion $C_k$ in the form of crisp number with $i \in M$, where $M = \{1,..,m\}$, $k \in N$, and $N = \{1,..,n\}$. The decision making procedure for TODIM method is described as follows:

**Step 1:** Calculate the relative weight $w_{kr}$ of criterion $C_k$ to the reference criterion $C_r$ as follows:

$$w_{kr} = \frac{w_k}{w_r} \tag{11}$$

where $w_k$ denotes the weight of the criterion $C_k$ and $w_r$ = max $\{w_k \mid k \in N)\}$.

**Step 2:** TODIM method relies on the dominance of one alternative $(A_i)$ over another alternative $(A_j)$ under criterion k calculated by using the value function of Prospect Theory expressed following:

$$\phi_k(A_i, A_j) = \begin{cases} \sqrt{\left|x_{ik} - x_{jk}\right| \dfrac{w_{kr}}{\sum_{k=1}^{n} w_{kr}}} & x_{ik} - x_{jk} > 0 \\ 0 & x_{ik} - x_{jk} = 0 \\ -\dfrac{1}{\theta}\sqrt{\left|x_{ik} - x_{jk}\right| \dfrac{\sum_{k=1}^{n} w_{kr}}{w_{kr}}} & x_{ik} - x_{jk} < 0 \end{cases} \tag{12}$$

where $\theta$ denotes attenuation factor that evaluate loss aversion. $\theta > 0$ represents high risk aversion preference of DM. If $\theta < 0$, less risk aversion or higher risk seeking attribute of DM reflected on ranking alternatives.

**Step 3:** Obtain the overall dominance degree of each alternative $A_i$ over each $A_j$ calculated by:

$$\phi\left(A_i, A_j\right) = \sum_{k=1}^{n} \phi_k(A_i, A_j) \qquad i, j \in M \;\&\; k \in N \tag{13}$$

**Step 4:** Calculate the global dominance of alternative $A_i$ as follows:

$$\xi(A_i) = \frac{\sum_{j=1}^{m} \phi\left(A_i, A_j\right) - \min \sum_{j=1}^{m} \phi\left(A_i, A_j\right)}{\max \sum_{j=1}^{m} \phi\left(A_i, A_j\right) - \min \sum_{j=1}^{m} \phi\left(A_i, A_j\right)} \qquad i \in M \tag{14}$$

**Step 5:** Calculation of the global dominance of each alternative makes possible to rank of alternatives. The alternative has higher value of $\xi$ is the best alternative.

**Decision-Making Process: Fuzzy TODIM based on α-Cuts to Select WWTP**

Since the classical MCDM tools do not consider the risk orientations of the decision makers, the situation arises that the model is inadequate in the face of dynamic changes[34]. Unforeseen parameters such as sudden population changes, epidemics, disasters, adverse conditions due to climate change, lack of space, cost of energy, cause the phenomenon that manages the uncertainty to be chosen according to the behavior of avoiding risk rather than avoiding loss. The form of this behavior in real life expressed as a function is the membership function of Prospect Theory. TODIM is a technique derived from Prospect Theory which puts the membership function of Prospect Theory at the center of the decision making process to reflect the rational behavior of DMs[35]. In this context, the framework for the decision making process including the weighting to obtain relative weights of criteria is retrieved from Fig. 3 and consists of three phases as can be seen in Fig. 4:

Phase-I: Figuration includes (a) defining an alternative sets (b) establishment of criteria system with respect to available technology of WWTP processing, (c) data collection from design engineer, construction engineer, process or operation engineer and environmental impact assessment expert, (d) priority evaluation of criteria and sub-criteria in terms of weight calculation through AHP.

Phase-II: Modelling and Evaluation composes of (a) data normalization procedure of TrFNs, (b) weighting of subjective judgements and objective data based on *α-cuts* and derived the membership function, (c) calculation of aggregate weights of criteria, (d) converting TrFNs into their upper and lower bounds to obtain their *α-cuts* for crisp data (e) obtaining the gains and losses, (f) calculating dominance of each alternatives based on the gains or losses, (g) evaluating overall dominance degree of alternatives, (h) calculating global dominance of alternatives.

Phase III: Selection encloses ranking of alternatives according to its global dominance degree at each alpha level sets. A solution environment will be provided to DMs in which they can evaluate the most compromised solution according to global dominance degree at each alpha level sets. In addition, presenting the average global dominance degrees considering alpha cuts guide DMs to choose the most consistent solution for process of WWTP.

**Data Transformation**

In order to, reflect the ambiguous nature of subjective judgements and uncertainty of inaccurate information, trapezoidal fuzzy numbers were used in decision model. Under the condition of symmetric uncertainty around the mean, crisp and linguistic data were changed into TrFNs. 20% of uncertainty to compose with trapezoidal fuzzy numbers and %5 of symmetric uncertainty around the mean calculated as follows: $a_1 = t - 0.2\,t,\ a_2 = t - 0.05\,t,\ \ a_{3} = t + 0.05\,t, a_{4} = t + 0.2\,t$ where $t$ denotes the collected crisp data value. Additionally, linguistic terms are transformed to TrFNs via their mapping relations showed in Table 2. Linguistic terms are determined by survey of wastewater treatment plant's operators and experts with respect to 1-10 scale.

| Linguistic Terms | 1-10 Scale |
|---|---|
| Extremely Poor (EP) | 1 |
| Very Poor (VP) | 2 |
| Fairly Poor (FP) | 3 |
| Poor (P) | 4 |
| Medium (M) | 5 |
| Fairly Strong (FS) | 6 |
| Strong (S) | 7 |
| Very Strong (VS) | 8 |
| Extremely Strong (ES) | 9,10 |
| | Trapezoidal Interval Fuzzy Number |
| EP | (0.8, 0.95, 1.05, 1,2) |
| VP | (1.6, 1.9, 2.1, 2.4) |
| FP | (2.4, 2.85, 3.15, 3.6) |
| P | (3.2, 3.8, 4.2, 4.8) |
| M | (4.0, 4.75, 5.25, 6.0) |
| FS | (4.8, 5.7, 6.3, 7.2) |
| VS | (5.6, 6.65, 7.35, 8.4) |
| ES | (6.4, 7.6, 8.4, 9.6) |
| | (7.2, 8.55, 9.45, 9.6); |
| | (8.0, 9.5, 10.5, 12,0) |

**Table 2.** Linguistic Terms and their expression based on TrFNs.

**Data Normalization**

To obtain normalized decision matrix, assume that there is an alternative set of $A = \{A_1, \dots, A_m\}$ including m alternatives, a criteria set of $C = \{C_1, \dots, C_n\}$ including n criteria, and the fuzzy decision matrix $\widetilde{A} = [\tilde{x}_{ij}]_{m\,x\,n}$ where $\tilde{x}_{ij}$ denotes the information of alternative $A_i$ related to criterion $C_j$ transformed into TrFNs. Then, the fuzzy decision matrix is converted into the normalized decision matrix as $\widetilde{A} = [\tilde{r}_{ij}]_{m\,x\,n}$. The criteria are separated into two groups benefit and cost criteria. The normalization of criteria is performed by:

$$\tilde{r}_{ij}^{k} = \frac{\max(a_{ij}^{4}) - a_{ij}^{k}}{max_i(a_{ij}^{4}) - min_i(a_{ij}^{1})} \qquad k = 1,2,3,4 \;\; x_{ij} \in F^{C}$$

$$\tilde{r}_{ij}^{k} = \frac{a_{ij}^{k} - min_i(a_{ij}^{1})}{max_i(a_{ij}^{4}) - min_i(a_{ij}^{1})} \qquad k = 1,2,3,4 \;\; x_{ij} \in F^{B}$$

(15)

**Determination of Criteria Weights**

In the decision model presented in this study, an aggregate weighting approach is proposed in order to include both subjective judgements and objective data. During the operation phase of wastewater treatment plants, both quantitative data and engineering experiences are taken into consideration while evaluating plant efficiency. The methodology is developed by Abdel-Kader and Dugdale[16] are employed to calculate final weight scoring of subjective judgement and objective data. The aggregated weight is calculated to obtain holistic approach for weighting by linear weighting method as follows:

$$w_{j\_agg} = \gamma w_{j\_sub} + \lambda w_{j\_ob} \qquad \gamma + \lambda = 1, and\; \gamma, \lambda > 0 \tag{16}$$

where $wj_{agg}$, $w_{j\_sub}$ , and $w_{j\_ob}$ are denoted aggregated weight, subjective weight and objective weight vectors respectively. In this study, γ and λ represents the influence coefficient of the subjective and objective weights, respectively which were assumed to be 0.5.

**Determination of Subjective Weights of Criteria**

In order to make a realistic criteria evaluation, it is necessary to deal with the ambiguity of subjective judgments and data inconsistencies. Hence, the effect of subjective judgment on the criteria is evaluated in two stages. In the first stage, the first weights of the criteria according to the priority evaluation performed by the experts are determined via AHP. The results of subjective judgements are represented in Table 3. The evaluation results of subjective judgements set is expressed $E = \{E_1, \dots, E_t\}$ and, t is the number of experts. A criteria set is defined as $C = \{C_1, \dots, C_n\}$ and, n is the number of criteria. The evaluated results through AHP are converted into the linear fuzzy weights of criteria expressed as $\widetilde{w}_E = [\widetilde{w}]_{t\,x\,n}$ . The normalized fuzzy weights are calculated by Eq. (15) according to the benefit and cost criteria. As the last phase, to keep uncertain environment as much as possible α-cut sets are employed rather than centroid method. The corresponding normalized fuzzy weights are expressed as α-cuts (α = { 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0}) by Eq. (9) [36].

| Criteria | Expert-1 | Expert-2 | Expert-3 | Expert-4 |
|---|---|---|---|---|
| C11 | 0.21 | 0.49 | 0.40 | 0.26 |
| C12 | 0.55 | 0.31 | 0.40 | 0.41 |
| C13 | 0.24 | 0.19 | 0.20 | 0.33 |
| C21 | 0.24 | 0.29 | 0.09 | 0.14 |
| C22 | 0.25 | 0.34 | 0.11 | 0.21 |
| C23 | 0.22 | 0.12 | 0.28 | 0.21 |
| C24 | 0.13 | 0.12 | 0.26 | 0.14 |
| C25 | 0.16 | 0.11 | 0.26 | 0.30 |
| C31 | 0.13 | 0.12 | 0.15 | 0.17 |
| C32 | 0.13 | 0.12 | 0.15 | 0.17 |
| C33 | 0.13 | 0.12 | 0.15 | 0.17 |
| C34 | 0.13 | 0.12 | 0.15 | 0.17 |
| C35 | 0.13 | 0.12 | 0.15 | 0.17 |
| C36 | 0.04 | 0.02 | 0.02 | 0.01 |
| C37 | 0.05 | 0.04 | 0.04 | 0.01 |
| C38 | 0.08 | 0.11 | 0.07 | 0.03 |
| C39 | 0.05 | 0.06 | 0.03 | 0.01 |
| C310 | 0.04 | 0.07 | 0.02 | 0.01 |
| C311 | 0.09 | 0.10 | 0.07 | 0.08 |
| C41 | 0.27 | 0.14 | 0.24 | 0.36 |
| C42 | 0.16 | 0.18 | 0.18 | 0.10 |
| C43 | 0.17 | 0.25 | 0.24 | 0.22 |
| C44 | 0.20 | 0.18 | 0.23 | 0.22 |
| C45 | 0.20 | 0.25 | 0.11 | 0.10 |
| $CI_{11-13}$ | 2.0% | 6.0% | 0.0% | 6.0% |
| $CI_{21-25}$ | 8.9% | 1.0% | 1.0% | 7.0% |
| $CI_{31-311}$ | 6.0% | 1.0% | 2.0% | 1.0% |
| $CI_{41-45}$ | 2.0% | 5.0% | 8.0% | 2.0% |

**Table 3.** Evaluation results of subjective judgements through AHP

In order to determine final weight scoring, a membership function is suggested which is derived from the methodology is developed by Abdel-Kader and Dugdale[16] to achieve final subjective weight scoring. The methodology is used in fuzzy multi-criteria decision making models based on α-cuts considering risk seeking or risk avoiding perspective of DMs which enables to compare solution set for compromise solutions[37]. The membership function for final weighting is as follows:

$$\mu_s(w_k)_\alpha = \left[\beta\left(\frac{(\tilde{x}_k)^U_\alpha - \min(\tilde{x}_k)^L}{\max(\tilde{x}_k)^U - \min(\tilde{x}_k)^L + (\tilde{x}_k)^U_\alpha - (\tilde{x}_k)^L_\alpha}\right)\right.$$

$$\left. + (1-\beta)\left(1 - \frac{\max(\tilde{x}_k)^U - (\tilde{x}_k)^L_\alpha}{\max(\tilde{x}_k)^U - \min(\tilde{x}_k)^L + (\tilde{x}_k)^U_\alpha - (\tilde{x}_k)^L_\alpha}\right)\right] \quad \left[\frac{(\tilde{x}_k)^U_\alpha + (\tilde{x}_k)^L_\alpha}{2}\right] \tag{17}$$

where $(\tilde{x})_\alpha$, = $[(x)^L_\alpha, (x)^U_\alpha]$ is the α-cuts of $\tilde{x}$ which denotes subjective criteria weights. The $\max(\tilde{x}_k)^U$ and, $\min(\tilde{x}_k)^L$ shows the value of the maximum upper, and minimum lower bound of $\tilde{x}$ related to criterion k among eleven alpha level sets (α-cuts) respectively. In the derived membership function, $\beta$ represents the risk tendencies of the decision makers (risk averse or risk seeking) and its value defined as 0.5. The calculated weights can be normalized as follows:

$$(w_k)_\alpha = \frac{(w_k)_\alpha}{\sum_{k=1}^{n}(w_k)_\alpha} \tag{18}$$

The results of normalized weights matrix of evaluated subjective judgements are represented in Supplementary Material section.

**Determination of Objective Weights of Criteria**

The evaluation of quantitative data gathering from operation department of WWTPs includes data transformation, normalization and, obtaining objective criteria weights phases. The approach to converting crisp values to TrFNs and normalization procedure is discussed in *Data Transformation* and *Data Normalization*, respectively.

As a final scoring of quantitative data to calculate compromise weighting vector based on α-cut sets Eq. (8) and Eq. (9) are employed with respect to eleven alpha levels, α = {0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0}. To obtain the decision weighting vector of quantitative data, the membership function and its normalized form is as follows:

$$\mu_o(w_{ik})_\alpha = \left[\beta\left(\frac{(\tilde{x}_{ik})^U_\alpha - \min(\tilde{x}_{ik})^L}{\max(\tilde{x}_{ik})^U - \min(\tilde{x}_{ik})^L + (\tilde{x}_{ik})^U_\alpha - (\tilde{x}_{ik})^L_\alpha}\right)\right.$$

$$\left. + (1-\beta)\left(1 - \frac{\max(\tilde{x\imath}_k)^U - (\tilde{x}\imath_k)^L_\alpha}{\max(\tilde{x}_{ik})^U - \min(\tilde{x}_{ik})^L + (\tilde{x}_{ik})^U_\alpha - (\tilde{x\imath}_k)^L_\alpha}\right)\right] \quad \left[\frac{(\tilde{x}_{ik})^U_\alpha + (\tilde{x\imath}_k)^L_\alpha}{2}\right] \tag{19}$$

where $(\tilde{x})_\alpha$, = $[(\tilde{x}_{ik})^L_\alpha, (\tilde{x}_{ik})^U_\alpha]$ is the α-cuts of $\tilde{x}$ which denotes quantitative criteria weights. The $\max(\tilde{x}_{ik})^U$ and, $\min(\tilde{x}_{ik})^L$ shows the value of the maximum upper, and minimum lower bound of $\tilde{x}_i$ represented performance of alternative $A_i$ related to criterion k among eleven alpha level sets (α-cuts) respectively. In the derived membership function, $\beta$ represents the risk tendencies of the decision makers (risk averse or risk seeking) and its value defined as 0.5. The calculated weights can be normalized as follows:

$$(w_k)_\alpha = \frac{(w_k)_\alpha}{\sum_{k=1}^{n}(w_k)_\alpha} \tag{20}$$

The results of normalized weights of quantitative data are available from Supplementary Material section.

**Dominance of Each Alternative**

The fuzzy TODIM approach is implemented with the fuzzy criterion weights and the distance calculation between two fuzzy numbers to obtain overall dominance degree of each alternative. Dominance of each alternative $\tilde{A}_i$ over each alternative $\tilde{A}_j$ is calculated by the membership function of Prospect Theory is based on gains or losses performed by trapezoidal fuzzy numbers to evaluate risk aversion degree in the presence of uncertain environment as follows.

$$\varphi_k(\tilde{A}_i, \check{A}_j) = \begin{cases} \sqrt{d(\tilde{x}_{ik}, \tilde{x}_{jk})\, \frac{w_{kr}}{\sum_{k=1}^{n} w_{kr}}} & if\ [S\,(\tilde{x}_{ik}) - S\,(\tilde{x}_{jk})] > 0, \\ 0 & if\ [S\,(\tilde{x}_{ik}) - S\,(\tilde{x}_{jk})] = 0,\ \ and \\ -\frac{1}{\theta}\sqrt{d(\tilde{x}_{ik}, \tilde{x}_{jk})\, \frac{\sum_{k=1}^{n} w_{kr}}{w_{kr}}} & if\ [S\,(\tilde{x}_{ik}) - S\,(\tilde{x}_{jk})] < 0. \end{cases} \tag{21}$$

$S\,(\tilde{x}_{ik})$ and $S\,(\tilde{x}_{jk})$ parameters are defuzzied values which allow to compare two trapezoidal fuzzy numbers for construction of final decision matrix according to defuzzification function expressed as $S\,(\tilde{x}_{ik}) - S\,(\tilde{x}_{jk})$. The expression $d(\tilde{x}_{ik}, \tilde{x}_{jk})$ is the distance between two trapezoidal fuzzy numbers. The defuzzification function employs to determine gain, loss or nil conditions. The use of the distance, $d(\tilde{x}_{ik}, \tilde{x}_{jk})$, to calculate dominance degree rather than defuzzification function appears logical, since the property $0 \leq d(\tilde{x}_{ik}, \tilde{x}_{jk}) \leq 1$ is satisfied. Three conditions are available in terms of gain or loss presented below. Gains, losses and nil are fitted into the membership function of Cumulative Prospect Theory as anticipated. The expression of $\varphi_k$ emphasizes contribution of the criterion k to function $\delta\,(\tilde{A}_i, \check{A}_j)$ when comparing the alternative i with j. $\theta$ denotes the attenuation factor of the loss. The value of $\theta$ should satisfy the condition $\theta > 0$, which indicates the degree of experts' loss averse preference. If $0 < \theta < 1$, then the impact of loss increases, if $\theta > 1$, the impact of loss decreases [38].

For attenuation factor $\theta$ which is taken 2.25 in this proposed decision framework:

i) $S\,(\tilde{x}_{ik})$- $S\,(\tilde{x}_{jk})$ > 0; Gain

ii) $S\,(\tilde{x}_{ik})$- $S\,(\tilde{x}_{jk})$ = 0; Nil

iii) $S\,(\tilde{x}_{ik})$- $S\,(\tilde{x}_{jk})$ < 0; Loss

The fuzzy TODIM based on α-cuts calculate dominance of each alternative according to different α-cuts of TrFNs and relative weights of criteria considering alpha level sets. To determine dominance degree of alternatives based on α-cut sets, gains and losses are calculated by upper and lower bounds of TrFNs instead of defuzzied values. On the other hand, for reliable and compromise ranking of alternative according to dominance degree is performed by interval of dominance degree rather than the distance calculation of two TrFNs. In order to realistic evaluation of criteria and expected alternative ranking fuzzy conditions should be preserved as much as possible in the decision process model. The α-cut are the effective forms of fuzzy sets to cope with uncertain environment along with decision process [39]. The expression of $(\tilde{x}_{ik})_\alpha$ and $(\tilde{x}_{jk})_\alpha$ are two intervals of TrFNs which are denoted as $(\tilde{x}_{ik})_\alpha = [(\tilde{x}_{ik})_\alpha^L, (\tilde{x}_{ik})_\alpha^U]$ and $(\tilde{x}_{jk})_\alpha = [(\tilde{x}_{jk})_\alpha^L, (\tilde{x}_{jk})_\alpha^U]$. The dominance degree of $(\tilde{x}_{ik})_\alpha$ over $(\tilde{x}_{jk})_\alpha$ are acquired by [40] is calculated by:

$$P\,((\tilde{x}_{ik})_\alpha > (\tilde{x}_{jk})_\alpha) = \frac{max\left[0, (\tilde{x}_{\mathrm{l}k})_\alpha^U - (\tilde{x}_{jk})_\alpha^L\right] - max\left[0, (\tilde{x}_{\mathrm{l}k})_\alpha^L - (\tilde{x}_{jk})_\alpha^U\right]}{\left[(\tilde{x}_{\mathrm{l}k})_\alpha^U - (\tilde{x}_{\mathrm{l}k})_\alpha^L\right] + \left[(\tilde{x}_{jk})_\alpha^U - (\tilde{x}_{jk})_\alpha^L\right]} \tag{22}$$

Gains and losses are expressed according to the following two conditions.

i) $P\,((\tilde{x}_{ik})_\alpha > (\tilde{x}_{jk})_\alpha) \geq P\,((\tilde{x}_{jk})_\alpha > (\tilde{x}_{ik})_\alpha);$

$$\rho_\alpha^+((\tilde{x}_{ik})_\alpha > (\tilde{x}_{jk})_\alpha) = P\,((\tilde{x}_{ik})_\alpha > (\tilde{x}_{jk})_\alpha) - P\,((\tilde{x}_{jk})_\alpha > (\tilde{x}_{ik})_\alpha)$$

ii) $P\,((\tilde{x}_{ik})_\alpha > (\tilde{x}_{jk})_\alpha) < P\,((\tilde{x}_{jk})_\alpha > (\tilde{x}_{ik})_\alpha);$

$$\rho_\alpha^-((\tilde{x}_{ik})_\alpha > (\tilde{x}_{jk})_\alpha) = P\,((\tilde{x}_{jk})_\alpha > (\tilde{x}_{ik})_\alpha) - P\,((\tilde{x}_{ik})_\alpha > (\tilde{x}_{jk})_\alpha)$$

(23)

where $\rho_\alpha^+((\tilde{x}_{ik})_\alpha > (\tilde{x}_{jk})_\alpha)$ and $\rho_\alpha^-((\tilde{x}_{ik})_\alpha > (\tilde{x}_{jk})_\alpha)$ denotes gains and losses respectively.

In this context, the dominance degree of alternative $A_i$ over $A_j$ with respect to criterion $C_k$ based on α-cut sets can be obtained by rearranging as follows.

$$\phi_k^\alpha(A_i, A_j) = \begin{cases} \sqrt{\rho_\alpha^+((\tilde{x}_{ik})_\alpha > (\tilde{x}_{jk})_\alpha)\ \dfrac{w_{kr}}{\sum_{k=1}^n w_{kr}}} & if\ \ P\,((\tilde{x}_{ik})_\alpha > (\tilde{x}_{jk})_\alpha) \geq P\,((\tilde{x}_{jk})_\alpha > (\tilde{x}_{ik})_\alpha) \\ -\dfrac{1}{\theta}\sqrt{\rho_\alpha^-((\tilde{x}_{ik})_\alpha > (\tilde{x}_{jk})_\alpha)\ \dfrac{\sum_{k=1}^n w_{kr}}{w_{kr}}} & if\ \ P\,((\tilde{x}_{ik})_\alpha > (\tilde{x}_{jk})_\alpha) < P\,((\tilde{x}_{jk})_\alpha > (\tilde{x}_{ik})_\alpha) \end{cases}$$

(24)

The overall dominance degree of alternative $\tilde{A}_\mathrm{i}$ over alternative $\tilde{A}_j$ is necessary to obtain *the global value of alternatives* that is calculated by:

$$\delta_\alpha(A_i, A_j) = \sum_{k=1}^{n} \phi_k^\alpha(A_i, A_j) \qquad \forall\ (i, j) \tag{25}$$

Where $\delta_\alpha(A_i, A_j)$ represents the measurement of overall dominance degree of alternative $A_i$ over alternative $A_j$ based on α-cuts, n is the number of criteria; k is any criterion for k = 1, …, n.

**Calculation of Global Dominance of Each Alternative**

The overall value of alternative i through normalization of the corresponding dominance measurements. The rank of each alternatives are determined the following equation that normalizes the overall dominance degree of alternatives to achieve eleven ranking set.

$$\xi_\alpha\,(A_i) = \frac{\sum_{j=1}^m \delta_\alpha(A_i, A_j)\ - \min \sum_{j=1}^m \delta_\alpha(A_i, A_j)}{\max \sum_{j=1}^m \delta_\alpha(A_i, A_j)\ -\ \min \sum_{j=1}^m \delta_\alpha(A_i, A_j)} \tag{26}$$

The overall dominance degree calculation based on α-cuts allows to choose the compromise ranking related risk seeking or risk averse choices through solution set. The advantage of the methodology is presented a solution set with respect to attenuation factor, θ to reflect risk perspective of DMs to the decision model and gives the best possible alternative according to the average global dominance degree, $\xi_{\alpha}(A_i)$. The average global dominance degree is calculated by:

$$\bar{\xi}(A_i) = \frac{1}{ß}\sum_{b=1}^{ß} \xi_{\alpha_b}(A_i), i = 1, \dots, m \qquad (27)$$

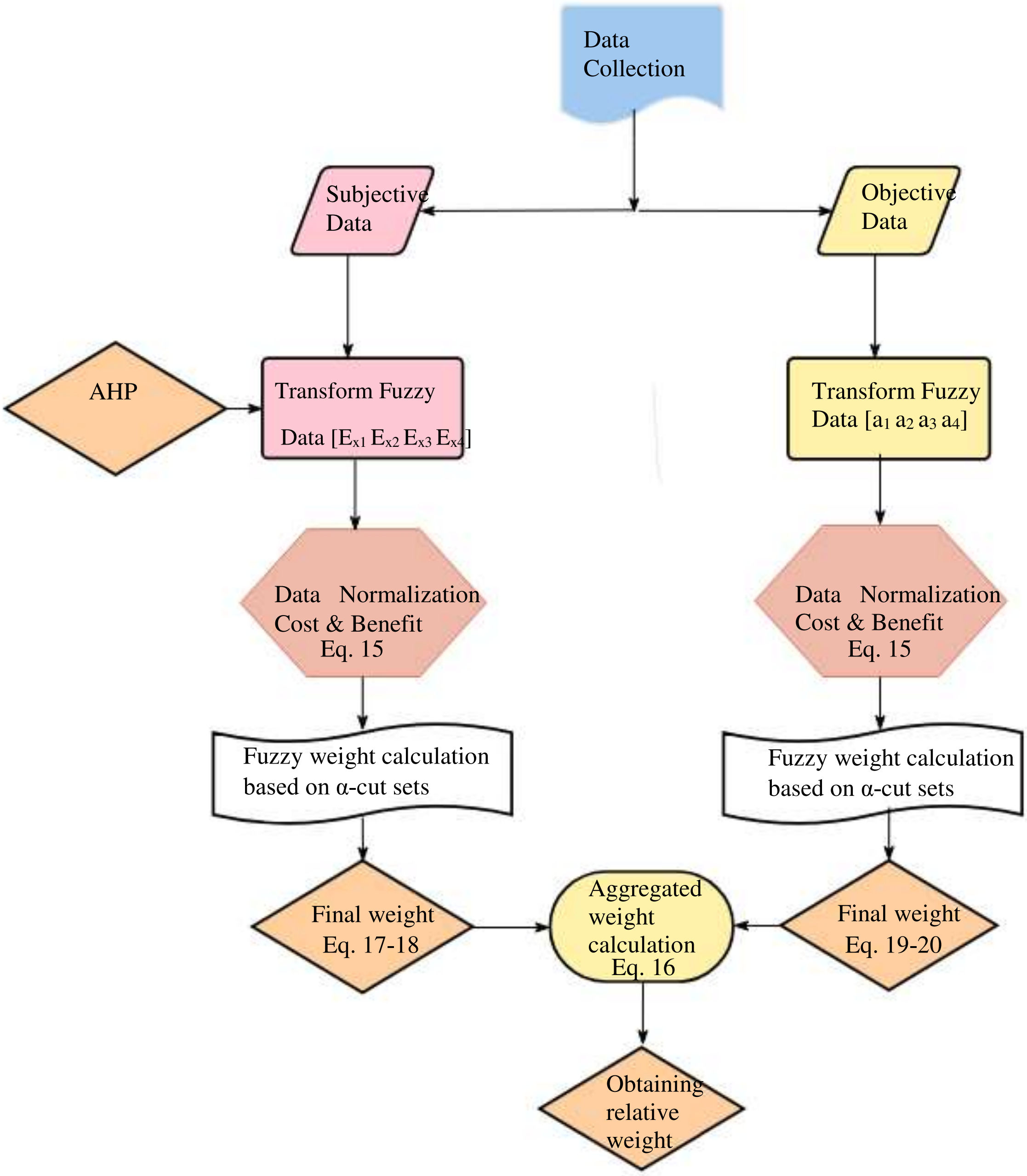


**Figure 3.** Creation of the weighted decision matrix

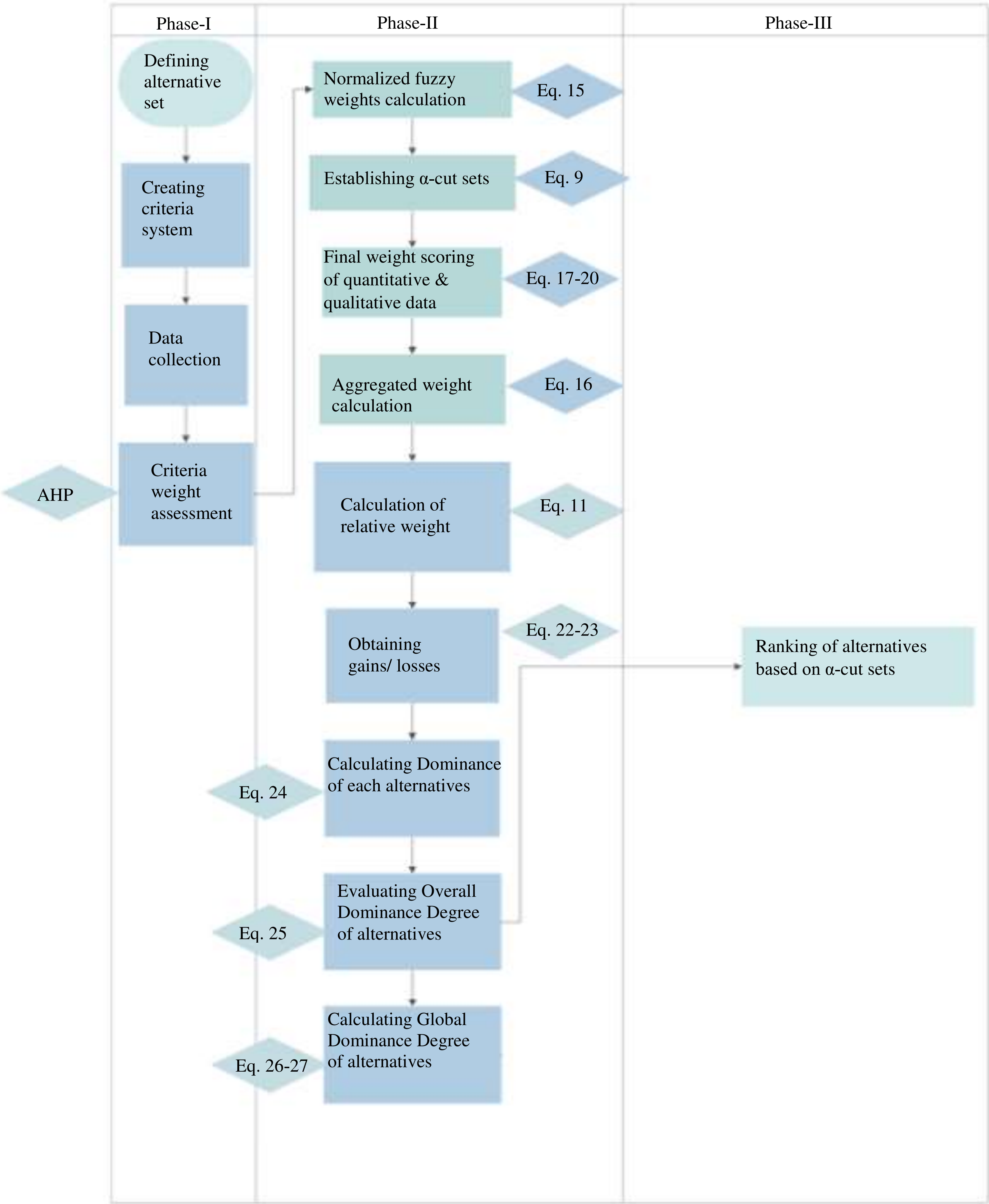




**Figure 4.** Decision making process in this study

## Case Study and Discussion

### Selection of Alternatives

The rapid progress of technological developments in the wastewater sector leads to differentiation of wastewater treatment technologies. Many authorities still prefer mature technologies for a variety of reasons such as lack of qualified personally, risk aversion, or outdated technical information. In Turkey the following treatment technologies are usually applied for WWTPs for plants having capacity of more than 100.000 $m^3$/ day (CAS-W/-P or CAS-W/O-P; A2O- W/-P or A2O-W/O-P; BP-5-W/-P or BP-5-W/O-P). In order to solve the possible infrastructure problems that Istanbul may encounter in the near future, high capacity WWTPs should be compared rationally. Based on this need, four types of wastewater treatment plants, which are of critical importance for Istanbul, were evaluated with a decision model, under the guidance of the sustainability concept taking into account the perception of experts. The alternatives are collected under four different process titles namely, CAS-W/-P (A1), A2O-W/O-P (A2), BP-5-W/-P (A3) and A2O W/-P (A4).

Conventional Activated Sludge System includes primary settling, aerobic biological treatment, secondary settling, disinfection, and discharge. It is commonly used as treatment technology for the removal of BOD and COD and, partial nutrient (N-nitrogen and P-phosphorus) removal can also be accomplished. Digester is required for this system since the sludge generated in CAS system is not stable.

A2O without Pre-clarification is a type of activated sludge process where a sequence of anaerobic, anoxic and aerobic tanks/zones are provided to remove organic carbon, nitrogen and phosphorus.

5-stage Bardenpho with Pre-clarification is an A2O process followed by a second anoxic zone and aerobic zone. Digester is used for the stabilization of sludge allowing a large fraction of the sludge organic matter to decompose under anaerobic conditions to carbon dioxide and methane.

A2O with pre-clarification is system where pre- clarification is followed by A2O system to remove organic carbon, nitrogen, and phosphorus [41]. Anaerobic digestion is used to stabilize the sludge coming from pre-clarification and final clarification units[42].

### Establishment of Decision Matrices

Since four different wastewater treatment plants, which are predicted to be of critical importance for Istanbul, are $A_1$, $A_2$, $A_3$ and $A_4$ as explained above, the set of alternatives is defined as $A = \{A_1, A_2, A_3, A_4\}$. In the decision model, four main criteria related to the sustainability aspects of WWTP technologies and 24 sub-criteria were determined as shown in Fig. 1, and the set of sub criteria is $C = \{C_1, C_2, \dots, C_{24}\}$. The crisp data obtained from real scale WWTPs belonging to sub-criteria are as listed in Table 4. The proposed fuzzy decision making framework comprises three main phases as namely data transformation, data normalization, and calculation of dominance of each alternatives to rank. The data transformation phase performed with two different approaches depending on the qualitative and quantitative criteria. For the crisp values of quantitative data are transformed to TrFNs with respect to 20% uncertainty of condition and 5% of symmetric uncertainty around the mean calculated by $a_1 = t - 0.2\,t,\ a_2 = t - 0.05\,t,\ a_3 = t + 0.05\,t,$ and $a_4 = t + 0.2\,t$.

The approach to transform qualitative data consists of two separate steps. First, subjective judgements are evaluated by AHP and, in the second part evaluated data are expressed with linear fuzzy weights. After the transformation phase, both the subjective and objective data is normalized in order to create decision matrix with normalized fuzzy weights. The normalized fuzzy weighting matrix is obtained by Eq. (15). Data normalization provides a classification of data as cost and benefit to provide data compatibility. Data transformation and data normalization matrices are available on Supplementary Information.

| Sub-criteria | Unit | Treatment Process Alternatives | | | |
|---|---|---|---|---|---|
| | | A1 | A2 | A3 | A4 |
| C11 | KW/year for 1 $m^3$ wastewater | 39,069,360 | 21,486,488 | 54,109,275 | 48,473,924 |
| C12 | kg/year for 1 $m^3$ wastewater | 30,996,000 | 51,963,177 | 111,795,652 | 34,414,044 |
| C13 | $m^3$ /year | - | 10,396,987 | 338,555 | 692,579 |
| C21 | USD | 138,650,000 | 140,000,000 | 133,318,000 | 155,197,000 |
| C22 | $m^2$ | 550,000 | 329,000 | 430,000 | 230,862 |
| C23 | USD/year for 1 $m^3$ wastewater | 6,500,000 | 4,700,000 | 8,500,000 | 6,000,000 |
| C24 | % | 42 | - | 40 | 57 |
| C25 | USD/kg-Year for 1 $m^3$ wastewater | 925,540.56 | 1,551,620.47 | 3,338,218.17 | 1,027,692.93 |
| C31 | | 94.2 | 96.3 | 92.6 | 97.0 |
| C32 | | 80.8 | 93.3 | 85.8 | 97.0 |
| C33 | % | 88.3 | 93.7 | 81.6 | 92.5 |
| C34 | | 74.7 | 89.0 | 56.8 | 75.0 |
| C35 | | 86.9 | 75.8 | 63.7 | 60.0 |
| C36 | | 5 | 7 | 8 | 7 |
| C37 | | 7 | 8 | 7 | 8 |
| C38 | | 2 | 8 | 8 | 8 |
| C39 | | 2 | 8 | 8 | 8 |
| C310 | | 8 | 9 | 8 | 9 |
| C311 | 1-10 scale | 6 | 10 | 9 | 10 |
| C41 | | 2 | 7 | 6 | 6 |
| C42 | | 7 | 8 | 7 | 7 |
| C43 | | 5 | 7 | 8 | 8 |
| C44 | | 6 | 8 | 8 | 8 |
| C45 | | 6 | 7 | 9 | 9 |

**Table 4.** Crisp and linguistic data of sub-criteria for WWTP Technology Selection Problem

## Analysis of the results

### Individual Weight of Criteria

In order to obtain relative criteria, an approached weight calculation is developed on the base of α-cut set, which is shown in Fig. 3. The final weighting calculation is a crucial role in reaching compromise solution by α-cut sets which is defined by the membership function of in Eq. (17)-(20). The weighting vectors at each alpha level incorporate the methodology discussed in *Determination of Criteria Weights* section depending on the optimism index of the DMs, in order to enable an evaluation of the weighting of subjective judgements and objective data related to risk reverse or risk seeking behavior. This weighting procedure contributes to a decision-making process that is compatible with the TODIM method. The relative weights of the aggregated weights to be used in the TODIM method used for ranking the alternatives are calculated according to Eq. (11). The individual or relative weight of criteria calculation necessitates ascertaining reference criteria. The individual weight of criteria employs the calculation of the dominance degree of alternatives. The obtained sets of aggregated criteria are shown in Fig. 5.

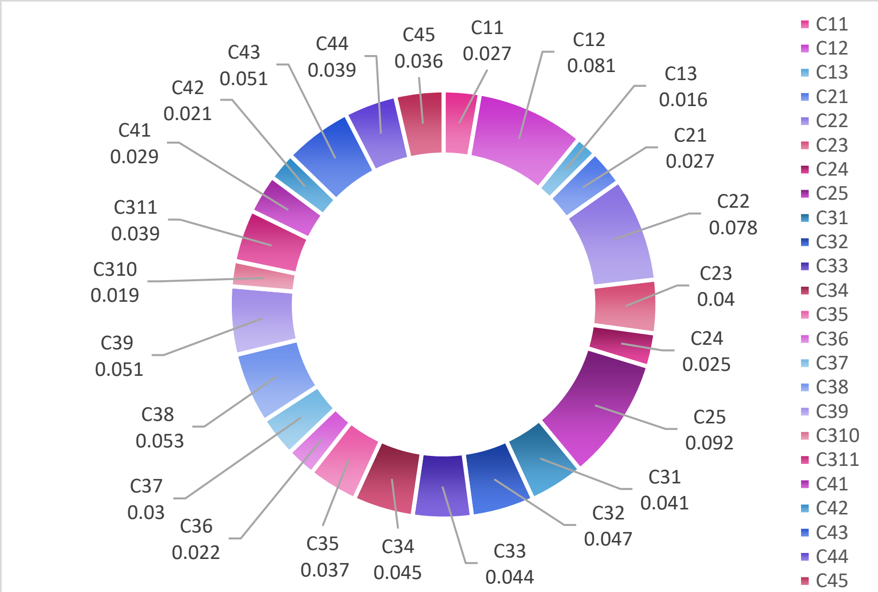


**Figure 5.** The aggregated criteria weights distributions. The aggregated weights of criteria employs to produce relative weight of each criterion provided ranking of the alternatives according to the loss-averse behavior of the DMs.

Such an approach allows a clear numerical demonstration of the dominance of one alternative over another. The aggregated weight with the highest value corresponds the reference criteria used to calculate relative weights. Fig. 5 clearly shows that the reference criterion (RC) had the highest aggregated weight C25 (sludge disposal cost). Another with higher aggregated weight is C12 (sludge generation). The weighting results show that sludge plays crucial role to select optimal alternative for WWTPs. In real life problem, sewage sludge is positioned as a by-product that is difficult to dispose of and high disposal costs as an insurmountable barrier. This point of view is effective in the subjective assessment of the experts and, due to the high sludge disposal costs, is also reflected in the weightings with quantitative data.

The dominance of the objective and subjective data weights, which are the components of the aggregated weights, when selecting the reference criterion is shown in Fig. 6 and Fig. 7. The graphic interpretation of the positions of the objective and subjective data weights according to the calculated reference criterion weight clearly demonstrates the dominant weight set based on α-cuts.

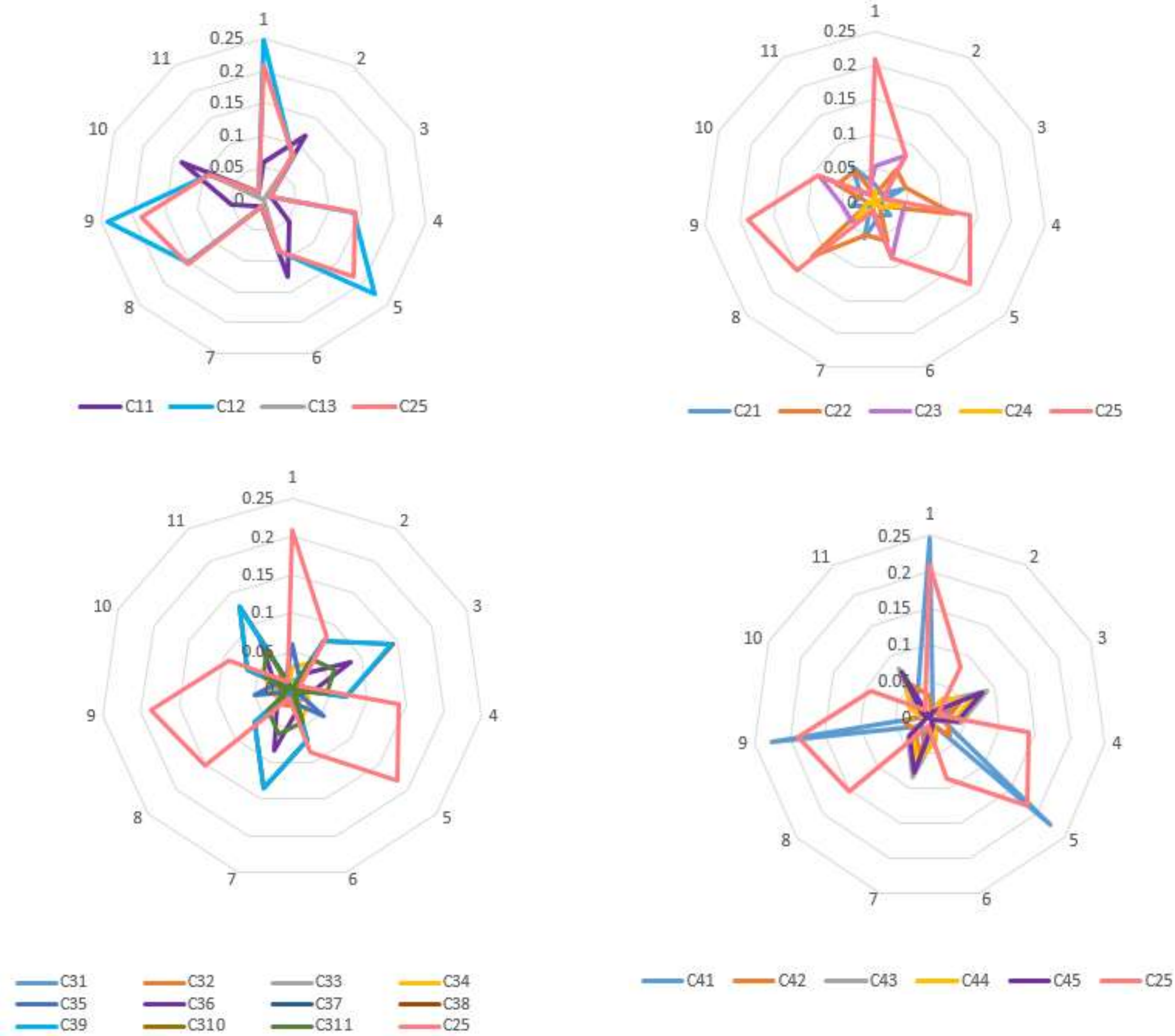


**Figure 6.** The objective weights relative to the reference criterion

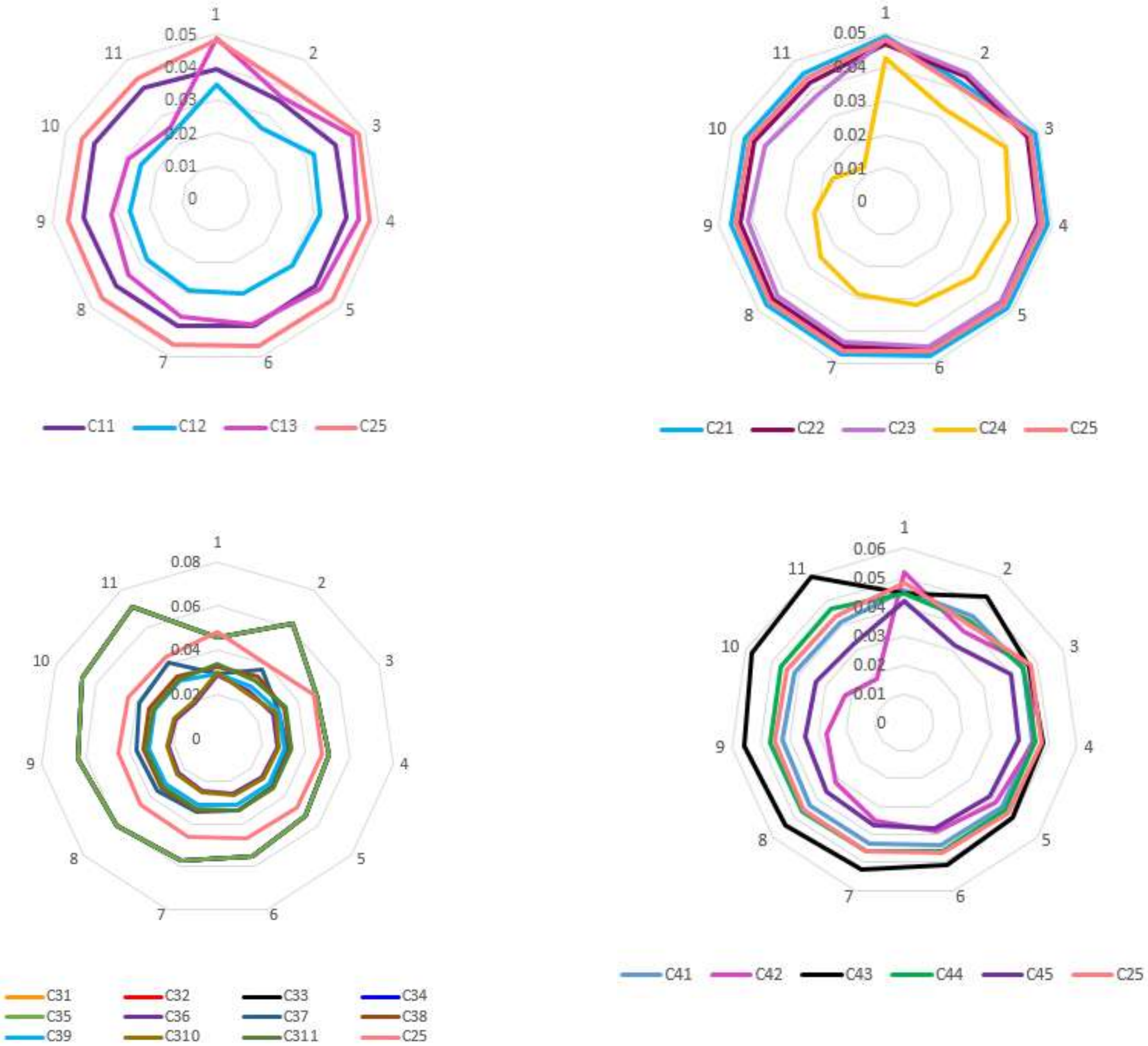


**Figure 7.** The status of each subjective weight relative to the reference criterion found.

**Calculation of the Global Dominance of Each Alternatives**

After completion the weighting phase of the decision-making process has been completed, to evaluate the most suitable process selection of WWTP, the global dominance degree is calculated. To achieve global dominance of alternatives the procedure summarized as follows.

i) According to the evaluate gain or loss condition through Eq. (23), gain or loss is calculated based on α-cuts by Eq. (22) and where $\theta = 2.25$.

ii) Obtaining the dominance of each alternatives from Eq. (24)

iii) Evaluating overall dominance degree of the alternatives Eq. (25)

iv) Calculating global dominance and average global dominance degree Eq. (26) and Eq. (27), respectively.

v) Ranking of alternatives.

The dominance degree matrix of comparison between two alternatives at each alpha level sets are shown below

$$\phi_1 = \begin{bmatrix} 0 & -3.1 & -4.4 & -1.4 \\ -11.8 & 0 & -10.7 & -6.7 \\ -4.7 & 0.8 & 0 & 0.8 \\ -10.3 & -2.2 & -5.8 & 0 \end{bmatrix} \quad \phi_2 = \begin{bmatrix} 0 & -3.5 & -4.5 & -1.4 \\ -12.7 & 0 & -11.6 & -7.0 \\ -7.0 & 0.31 & 0 & 0.82 \\ -11.6 & -2.8 & -6.2 & 0 \end{bmatrix}$$

$$\phi_3 = \begin{bmatrix} 0 & -3.9 & -4.8 & -1.9 \\ -13.0 & 0 & -12.5 & -7.4 \\ -8.4 & 0.11 & 0 & 0.92 \\ -12.7 & -3.4 & -7.3 & 0 \end{bmatrix} \quad \phi_4 = \begin{bmatrix} 0 & -4.2 & -5.5 & -2.2 \\ -16.0 & 0 & -13 & -7.8 \\ -9.6 & -0.04 & 0 & 1.04 \\ -14.4 & -4.02 & -8.6 & 0 \end{bmatrix}$$

$$\phi_5 = \begin{bmatrix} 0 & -4.6 & -6.7 & -2.5 \\ -18 & 0 & -14 & -8.3 \\ -11.0 & -0.18 & 0 & 1.15 \\ -16.9 & -4.6 & -9.7 & 0 \end{bmatrix} \quad \phi_6 = \begin{bmatrix} 0 & -5.3 & -8.4 & -2.7 \\ -20.5 & 0 & -16 & -8.9 \\ -12.9 & -0.3 & 0 & 1.3 \\ -19 & -5.2 & -11.4 & 0 \end{bmatrix}$$

$$\phi_7 = \begin{bmatrix} 0 & -5.9 & -10 & -3.0 \\ -23 & 0 & -17.8 & -10 \\ -15 & -1.0 & 0 & 1.5 \\ -22 & -6.5 & -13 & 0 \end{bmatrix} \quad \phi_8 = \begin{bmatrix} 0 & -6.7 & -11.5 & -4.1 \\ -26 & 0 & -20 & -12 \\ -17 & -1.5 & 0 & 1.7 \\ -25 & -7.5 & -15 & 0 \end{bmatrix}$$

$$\phi_9 = \begin{bmatrix} 0 & -7.6 & -13 & -4.9 \\ -30 & 0 & -22.5 & -14 \\ -20 & -1.8 & 0 & 1.9 \\ -28.5 & -8.7 & -17 & 0 \end{bmatrix} \phi_{10} = \begin{bmatrix} 0 & -9.2 & -15.5 & -5.8 \\ -36.0 & 0 & -27.0 & -16.0 \\ -23.0 & -4.0 & 0 & 1.09 \\ -33.4 & -2.2 & -5.8 & 0 \end{bmatrix}$$

$$\phi_{11} = \begin{bmatrix} 0 & -12.1 & -18.5 & -7.7 \\ -44.7 & 0 & -33.6 & -19.7 \\ -27.7 & -7.3 & 0 & 0.3 \\ -41.7 & -15.5 & -27.4 & 0 \end{bmatrix}$$

This overall dominance results are discussed with the graphical demonstration in Fig. 8 in terms of gain and loss calculation via Eq. (24).

The overall dominance degree $\delta(A_i)$ of alternative $A_i$ is calculated by using Eq. (25) and $\delta(A_i)$ are obtained as follows:

$\delta_1(A_1)$ =-8.9; $\delta_1(A_2)$ =-29.2; $\delta_1(A_3)$ =-3.1; $\delta_1(A_4)$ =-18.3

$\delta_2(A_1)$ =-9.4; $\delta_2(A_2)$ =-31.3; $\delta_2(A_3)$ =-5.87; $\delta_2(A_4)$ =-20.6

$\delta_3(A_1)$ =-10.6; $\delta_3(A_2)$ =-32.9; $\delta_3(A_3)$ =-7.37; $\delta_3(A_4)$ =-23.4

$\delta_4(A_1)$ =-11.9; $\delta_4(A_2)$ =-36.8; $\delta_4(A_3)$ =-8.6; $\delta_4(A_4)$ =-27

$\delta_5(A_1)$ =-13.8; $\delta_5(A_2)$ =-40.3; $\delta_5(A_3)$ =-10.3; $\delta_5(A_4)$ =-31.2

$\delta_6(A_1)$ =-16.4; $\delta_6(A_2)$ =-45.5; $\delta_6(A_3)$ =-11.9; $\delta_6(A_4)$ =-35.6

$\delta_7(A_1)$ =-18.9; $\delta_7(A_2)$ =-40.3; $\delta_7(A_3)$ =-13.5; $\delta_7(A_4)$ =-31.2

$\delta_8(A_1)$ =-22.3; $\delta_8(A_2)$ =-58.0; $\delta_8(A_3)$ =-16.8; $\delta_8(A_4)$ =-47.5

$\delta_9(A_1)$ =-25.5; $\delta_9(A_2)$ =-66.5; $\delta_9(A_3)$ =-19.9; $\delta_9(A_4)$ =-54.2

$\delta_{10}(A_1)$ =-30.5; $\delta_{10}(A_2)$ =-79.0; $\delta_{10}(A_3)$ =-25.9; $\delta_{10}(A_4)$ =-41.4

$\delta_{11}(A_1)$ =-38.3; $\delta_{11}(A_2)$ =-9.8; $\delta_{11}(A_3)$ =-34.7; $\delta_{11}(A_4)$ =-84.6

The global dominance of the alternatives is determined according to Eq. (26) considering $\delta_\alpha(A_i, A_j)$ function and by aligning the global dominance according to $\delta_\alpha(A_i, A_j)$function. It facilitated ranking of alternatives with respect to overall dominance degrees that represented in Table 5.

| | | | | | α | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $\xi_\alpha(A_i)$ | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
| A1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| A2 | 1 | 1 | 1 | 1 | 1 | 0.989 | 0.971 | 0.977 | 0.98 | 0.95 |
| A3 | 0.242 | 0.33 | 0.346 | 0.373 | 0.395 | 0.378 | 0.384 | 0.391 | 0.4 | 0.41 |
| A4 | 0.868 | 0.93 | 0.95 | 0.973 | 0.993 | 1 | 1 | 1 | 1 | 1 |
| Rank | **2-4-3-1** | **2-4-3-1** | **2-4-3-1** | **2-4-3-1** | **2-4-3-1** | **4-2-3-1** | **4-2-3-1** | **4-2-3-1** | **4-2-3-1** | **4-2-3-1** |

**Table 5.** The global dominance of alternatives for each α-cuts and rank of the alternatives for θ =2.25.

The expression $\delta_\alpha(\widetilde{A}_i, \breve{A}_j)$ indicates the performance of each alternative based on each sub-criteria and the superiority of $A_i$ over $A_j$ for each α-cuts.

The global values $\xi_\alpha(A_i)$ allows a clear ordering for appropriate selection. To compare alternative i with alternative j, the function $\delta_\alpha(A_i, A_j)$ can be used, which is a value function and is expressed by computing $\phi_k^\alpha(A_i, A_j)$ will. The determination of global dominance is carried out in two ways in order to obtain a compromise solution. First, the global degree is calculated using α-cut sets, the ranking options for selecting suitable WWTPs depending on the DM perspective. The second is to calculate the average global dominance to demonstrate the possible optimal set of solutions. The results show that the ranking of the alternatives based on the average global dominance degree for the selection of the WWTP process is: **$A_2$> $A_4$> $A_3$> $A_1$**. The average global dominance degree is calculated as $\bar{\xi}(A_i) = \{0, 0.979, 0.384, 0.975\}$.

In order to deal with the uncertainty that arises from subjective judgments and incomplete information that may be contained in the objective data, an effort id made to maintain the uncertain conditions until the end of the decision-making process by using the data presented with TrFNs were fuzzified and, alpha cut series without defuzzification.. The model offers decision makers the opportunity to choose according to risk-taking or risk-avoidance behavior. The average global dominance degree of alternatives ranks the alternatives depends on the attenuation factor $(\theta)$, which reflects the DM's point of view regarding risk aversion or risk seeking behavior.

## Discussion

In real life scenarios, dynamic environmental conditions lead to urgent decisions that may affect the psychological base behind behavior of DMs[43]. Thankfully, limitations such as governmental regulations, limited investment cost, compelling features of energy recovery, or sludge disposal can facilitate standardization the perception of risk in technology selection for wastewater treatment plants[44]. Determining the criteria that affect the perception of risk can ensure that the decisions are more rational and compatible with real cases. From this vantage point, the current study proposes a systematic approach that reflecting the decision making mechanism of risk aversion and revealing criteria set that manipulate the risk perception of DMs. By calculating the dominance degree of the alternatives, it is shown that the model enables options to rank alternatives in terms of risk-seekers or risk aversion behavior of DMs. The results showed that the decision maker's attitude towards risk aversion or risk-seeking the model predicts the cost of sludge disposal (C25) as the reference criterion. When calculating the dominance degree of the alternatives, it is shown that the model eliminates the choices in the risk-seeking tendency and highlights the gain values in the risk aversion tendency as shown in Fig. 8. The model performs by determining the dominance degrees depending on gain values of the criteria that fit into the sigmoidal function (S-shaped) for choices that tend to risk-averse, while reducing the effectiveness of the loss values that tend to risk –seeking. As a result, the criteria that have a high weight in the selections with a tendency of risk aversion come to the fore and determine the dominance degree of alternatives. Our results implies that alternative $A_2$ (A2O without pre-clarification) is the optimal technology of wastewater treatment plants in terms of sustainability. According to the current decision process based on the sustainability perspective, ''A2O without pre-clarification'' has emerged as the most ideal and sustainable process according to risk aversion approach. Sludge disposal cost (C25), which is the most effective criterion in this decision process, also plays a key role in real-life risk-oriented technology choices for wastewater treatment.

Sludge, which is recognized as an environmental problem due to the difficulties in disposal for WWTPs, is one of the main factor affecting the energy savings amounts, operational and maintenance problems and operating costs in the facilities[45]. Taking everything into consideration, the proposed decision process reveals a realistic ranking for technology selection of WWTPs rather than ideal one. Although, in real life, the investment costs are considered more in the design or operation of the WWTPs in the risk-avoidance choices of the decision makers, it emerges in a systematic decision making approach supported by scientific methods that the determining criteria should be environmental factors such as sludge for the implementation of correct sustainability policies.

## Sensitivity and Comparative Analysis

The sensitivity analysis was performed by changing the value of θ in order to obtaining comparative results regarding the risk aversion or risk seeking trend of DMs[46]. Table 6 shows the variations in the results along with θ values and average global dominance degree of alternatives and, ranking.

| **θ** | $\xi_i$ | | | | **Ranking of Alternatives** |
|---|---|---|---|---|---|
| | $A_1$ | $A_2$ | $A_3$ | $A_4$ | |
| 0.1 | 0 | 0.982 | 0.416 | 0.973 | **$A_2$> $A_4$> $A_3$> $A_1$** |
| 1 | 0 | 0.981 | 0.402 | 0.974 | **$A_2$> $A_4$> $A_3$> $A_1$** |
| 2 | 0 | 0.980 | 0.388 | 0.975 | **$A_2$> $A_4$> $A_3$> $A_1$** |
| 2.25 | 0 | 0.979 | 0.384 | 0.975 | **$A_2$> $A_4$> $A_3$> $A_1$** |
| 3 | 0 | 0.978 | 0.374 | 0.976 | **$A_2$> $A_4$> $A_3$> $A_1$** |
| 4 | 0 | 0.977 | 0.360 | 0.976 | **$A_2$> $A_4$> $A_3$> $A_1$** |
| 5 | 0 | 0.976 | 0.347 | 0.977 | **$A_4$> $A_2$> $A_3$> $A_1$** |
| 10 | 0 | 0.970 | 0.285 | 0.979 | **$A_4$> $A_2$> $A_3$> $A_1$** |

**Table 6.** The sensitivity analysis changing θ value

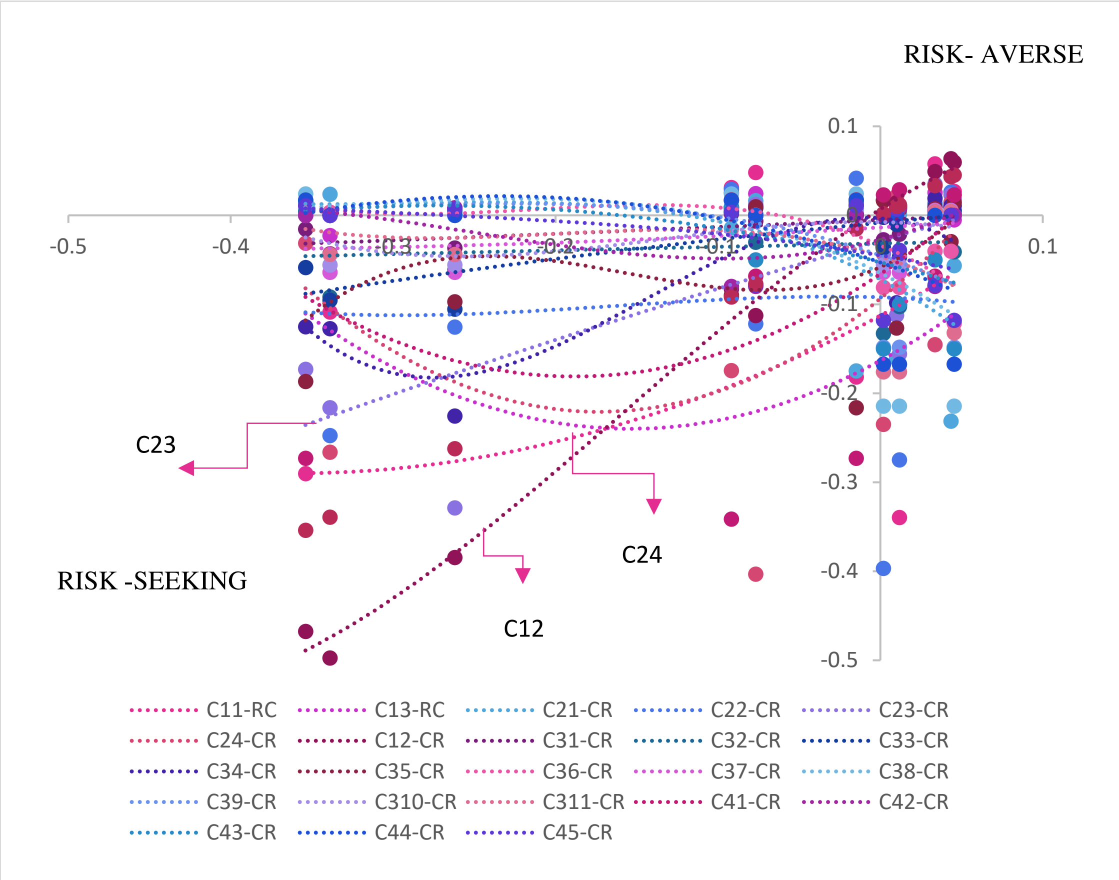


**Figure 8.** Risk-averse and risk seeking trend curves of criteria. Risk seeking and risk averse curves were obtained from the relative dominance degree of one alternative over other related to criteria to show how criteria impacts the overall dominance degree of alternatives. According to the reference criterion (C25) operational and maintenance cost (C23), energy savings (C24) and sludge generation (C12) criteria have the greatest influence on the determination of the overall dominance degree according to gain and loss value of criteria.

The sensitivity analysis results in Table 6 show that the difference between the global dominance degree of competing alternatives $A_2$ and $A_4$ is increase with respect to smaller risk aversion perception. The value of $\theta$ shows that the different psychological behavior in terms of risk aversion. The smaller $\theta$ expresses that a more risk averse behavior manages the ranking of alternatives. For example, $\theta$=0.1 means that a higher risk aversion is indicated and $\theta$=10 the experts prepare to taking risks so that the risk-seeking behavior manipulates the decisions. For this reason, the proposed decision-making model leads to consistent results according to the sensitivity analysis. While the compromise solution for a decision maker with a risk-seeking perspective is *2>4>3>1* for the optimal process selection of wastewater treatment plant, the result for a decision-maker with a risk-seeking perspective changes as *4>2>3>1*.

For the comparative study, TOPSIS, fuzzy TOPSIS and, intuitionistic TOPSIS and, intuitionistic VIKOR were used. Fuzzy TOPSIS under TrFN was applied for the comparative analysis[27]. Fuzzy TOPSIS is a methodology to rank of alternatives based on calculation of shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution[47]. After the normalization process of the qualitative and quantitative data, the weights of which are calculated by expressing with TrFNs, the fuzzy TOPSIS method leads to the calculation of the positive fuzzy ideal solution and the fuzzy negative ideal solution. The distance of each alternative from the fuzzy positive ideal solution and the fuzzy negative ideal solution is calculated, and the alternatives are ranked according to their closeness coefficients values. A detailed procedure of fuzzy TOPSIS under the TrFN can be referred to[48]. In addition, in order to demonstrate the sensitivity of the proposed extended fuzzy TODIM methodology, the intuitionistic VIKOR (IF-VIKOR) and the intuitionistic TOPSIS (IF-TOPSIS) method are applied to the procedure introduced by Alkafaas et al. in 2020[49] and Uyanik et al. in 2020[50]. The comparison of ranking results are represented in Table 7. The main factor of comparative analysis revealed reasonable output due to both of methods based on reference dependent approach and distance calculation.

| | TOPSIS | F-TOPSIS | IF-TOPSIS | IF-VIKOR |
|---|---|---|---|---|
| | $CC_i$ | $CC_i$ | $C_i$ | Q |
| $A_1$ | 0.528 | 0.530 | 0.9208 | 0.9972 |
| $A_2$ | 0.659 | 0.584 | 0.9318 | 0.0018 |
| $A_3$ | 0.336 | 0.223 | 0.9280 | 0.7432 |
| $A_4$ | 0.544 | 0.558 | 0.9367 | 0.5000 |
| Rank | **$A_2 > A_4 > A_1 > A_3$** | **$A_2 > A_4 > A_1 > A_3$** | **$A_4 > A_2 > A_3 > A_1$** | **$A_2 > A_4 > A_3 > A_1$** |

**Table 7.** The sensitivity analysis performed by TOPSIS, fuzzy TOPSIS, IF TOPSIS and, IF VIKOR

Proposed model in this study reflects much more clear the dominance of the alternatives with respect to psychological behavior over each other comparing with TOPSIS and fuzzy TOPSIS. In the comparative study performed with the IF-TOPSIS and IF-VIKOR methods, IF-TOPSIS revealed the same ranking of risk-seeking behavior in the ranking of the competing alternatives $A_2$ and $A_4$ compared to the method we proposed, while IF-VIKOR produced a similar ranking with less risk-aversion psychological behavior.

## Conclusion and Future Studies

The increasing importance of sustainable urbanization in developing countries and the rapid depletion of resources with the increasing population require a rational assessment of the need for WWTPs and the sustainability of existing facilities in order to minimize the risks arising from the possible water crisis in the near future. In this study, we introduce a framework presented a comparable analysis for the selection of WWTP technologies that could be applied on metropolitan cities by making use of fuzzy based decision making model by considering essentials of sustainability. The main conclusions of proposed decision making framework are summarized as below:

(1) The problem of technology selection for wastewater treatment plants is evaluated with a holistic approach by considering the environmental, economic, technical and social aspects of sustainability.

(2) According to the risk-oriented approach, the economic criteria have the biggest weight in the model, sludge disposal cost, which is a sub-criterion of economic factors, has become the prominent criterion to compare the relative dominance of alternatives.

(3) Heterogeneous data including both qualitative and quantitative data were normalized in the fuzzy environment to employ in the proposed decision model. To the best of our knowledge, our study is the first to pursue the

best compromise solution for the technology selection of WWTPs by using a risk-oriented decision-making methodology combined with TrFNs and considering the psychological behavior of DMs.

(4) The performance indicators were assessed to support decision-making procedure operated with TODIM methodology under fuzzy environment, which seems to offer the most appropriate decision making strategy based on behavioral characteristics of DMs and considering emergencies to effectively control decision making.

(5) Using a methodology based on fuzzy and risk oriented decision making provided an opportunity to include not only objective data such as inaccurate or insufficient technical information but also subjective judgements of DMs related to personal experience or knowledge and awareness level into decision-making process.

As a future work, the proposed decision-making procedure can be evaluated under the intuitionistic fuzzy environment to express the uncertainty of decision information coming from subjective judgements and improved in order to rank alternatives and hybrid models can be conducted to compare of water/wastewater treatment processes. The proposed decision model, will guide decision makers by making rational risk assessments under uncertainty by using the natural mechanism of human behavior in decision-making problems encountered in real life.

## Declaration

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## Authorship contributions

**Güneş Eseoğlu:** Investigation, Methodology, Software, Writing and original draft. **Kozet Yapsakli:** Supervision, conceptualization, formal analysis, writing and editing. **Hakan Tozan:** Validation and editing. **Özalp Vayvay:** Audit, Supervision, review.

## Appendix Supplementary Data

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- 7.5.SupplementaryNormalizedobjective.docx
- 7.6.Normalizedweightabdelkaderobjectivefunction.docx
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