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Abstract
Wastewater Treatment (WWT) for water reuse applications has been accepted as a strategic solution in improving water supplies across the globe; however, there are still various challenges that should be overcome. Selection of practical solutions is then

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required whilst considering technical, environmental, socio-cultural, and financial factors. In this study, a multi expert decision support tool that considers a variety of evaluation criteria is proposed to provide a ranking system for competing advanced WWT technologies in terms of their performance. Two scenarios of water reuse in the contexts of Brazil and Greece are defined, and evaluation is undertaken based on opinions of water reuse experts. The results prove that the tool would successfully facilitate rigorous and methodical analysis in evaluation of WWT technologies for water reuse applications with potential for use under various sets of evaluation criteria, WWT technologies and contexts.

**Keywords:** Water reuse; technology selection; group decision making; membrane technologies; environmental impacts

1 Introduction

The global population has doubled to seven billion people in half a century, placing considerable pressure on water resources. It is projected that by 2025, 67% of the global population will face significant water stress and 35% will suffer high constraints in accessing fresh water (Lazarova et al., 2001). Additionally, it is predicted that in the coming decades crowded urban settlements, that will generate heavy loads of water pollutants, will form a large proportion of the habitable world with higher levels of water withdrawal both for domestic and industrial use (Rosegrant et al., 2011). One potential solution to reducing water stress would be the application of water reuse technologies. Water reuse both augments opportunities for natural water quality improvement and improves management of competitive water demands.

There have already been various configurations of Wastewater Treatment (WWT) trains (Joksimovic et al., 2006), including membrane-assisted technologies, that have been acknowledged as suitable and reliable solutions regarding the removal of emerging pollutants and have been capable of meeting different water reuse standards (Dogan et al., 2016). However, the complexity of the advanced unit processes, together with solution variety, requires a systematic assessment so as optimum solutions are able to be identified and selected. In fact, to find a practical solution is often rather complex, as a wide range of decision requirements and uncertain conditions should be taken into account (Dheena and Mohanraj, 2011).

Regulations have also been an important obstacle to water reuse implementation (Casani et al., 2005), as they can significantly affect the number and type of solutions
and further complicate the process of decision making. This has recently received more
attention from the stakeholders and a number of regional, national, and international
guidelines or regulations have been established; for example, the World Health
Organisation (WHO) has published a number of guidelines on water reuse (for both non-
potable and potable water) and wastewater management (WHO, 2017, 2006a, 2006b).
Another well-established water reuse guidelines are developed by the US Environmental
Protection Agency (USEPA) (USEPA, 2012). A number of countries, such as India and
China, have issued their own national water reuse standards/regulations (Eldho, 2014;
Sadr et al., 2018; Yi et al., 2011; Zhu and Dou, 2018), however, in many other countries,
local regulators still develop their own water reuse standards on a “case-by-case” basis
(Casani et al., 2005).

Multi-Criteria Decision Analysis (MCDA) is a well-established decision support method
that strives to model expert thoughts and reasoning, and illustrates modelled results by
systematic procedures (Cakir and Canbolat, 2008), whilst evaluating a number of
solutions based on a set of criteria (Walker et al., 2015) with respect to economic,
environmental, social and technical aspects (Sadr et al., 2015). Decisions, involving
various issues, in particular environmental concerns and their associated policies and
regulations, oblige the participation of multiple stakeholders, as these decisions may
have both local and global impacts on the environment and/or the society (Kalbar et al.,
2013). To this end, the aim of any group decision activity is to identify the alternatives
that are assessed by a set of individuals as the optimum ones. To achieve a more
realistic approach, the experts are asked to assess not only the range of ‘agree-disagree’
but also they are requested to provide intermediate degrees as well, corresponding to
partial agreement (Bordogna et al., 1997).

Taking into account the fuzziness in Group Decision Making (GDM) and the fact that the
main contributors are experts, linguistic values can be employed, instead of numerical
ones. These values are used both for assigning the weights of criteria and for evaluating
each alternative against different criteria. Multi-Criteria Multi-Expert Decision Making
(MCMEDM) has already been proved to be a useful tool to achieve rankings based on
experts’ judgement (Chen, 2001, 2000). In GDM, the approaches that are adopted for
the aggregation of experts’ opinions play a major role (Fan and Liu, 2010). Technique
for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Analytic Hierarchy
Process (AHP) are commonly employed in the MCDA models and tools (especially for
GDM) (Agrawal et al., 2016; Behzadian et al., 2012; Jaiswal and Mishra, 2017; Zyoud et
al., 2016). TOPSIS is the most preferred method when decision problems involve large
numbers of criteria and technologies, especially if there are bits of quantitative information in the data (Kalbar et al., 2013); whereas, the AHP is a quite powerful technique when the criteria function autonomously (Behzadian et al., 2012). Hybrid models/tools of TOPSIS and AHP have also been developed and applied to different fields (Ertugrul, 2011; Jolai et al., 2011; Tavana and Hatami-Marbini, 2011; Yousefi and Hadi-Vencheh, 2010). To date and to the best of the authors’ knowledge, only few pieces of research focused on fuzzy based TOPSIS-AHP group decision making (i.e. multi-expert decision making) in wastewater treatment and water reuse applications (Kamble et al., 2017; Karahalios, 2017; Zyoud et al., 2016).

This study builds on the work previously presented by Sadr et al., (2015), which adapted an MCMEDM (fuzzy-TOPSIS) for the selection of WWT options in different water reuse situations. In brief, Sadr et al., (2015) addressed a number of critical challenges in water reuse technology selection; namely: (1) alleviated the challenges of using linguistic variables, (2) incorporated opinions of different stakeholders in a panel of decision-making, (3) Showed how to deal with numerous water reuse aspects, criteria, and technologies, and finally, (4) systematised and classified the plethora of information about water reuse scenarios, criteria, and technologies.

In this work, we implemented an improved GDM method via integrating fuzzy TOPSIS with AHP for the selection of WWT technologies for non-potable water reuse applications in different contexts with distinct regulations and different geographical, environmental, economic and demographic conditions. The approach was tested and validated by application to two case studies: (1) in São Paulo, Brazil, and (2) in Herakleion, Greece.

2 Methodology

Based on the lessons learnt from the previous study, we aimed to conduct this study in six phases (see Figure 1). The first phase develops an improved version of MCMEDM (i.e. IMCMEDM) in order to evaluate membrane-assisted water reuse technologies. The second phase involves the development of water reuse scenarios in the contexts of Brazil and Greece. Part of this phase is to identify and delineate the regions as local for water reuse application. It also explores the existing regulations, guidelines and standards for wastewater treatment and water reuse in those regions and develops a database that enables the comparison and assessment of alternatives. Next two phases, the third and fourth, identify the most important water reuse criteria and develop a list of possible WWT technologies, respectively. The fifth phase involves designing and subsequently distributing surveys on WWT criteria and technologies, whilst the sixth and
final phase aims at incorporating the thoughts of experts into the technology selection process (presented in the Result and Discussion Section).

**Figure 1:** The six phases towards selection of wastewater treatment technologies for different water reuse scenarios

### 2.1 Phase 1: Improved MCMEDM Method for multi expert technology selection

The improved MCMEDM (IMCMEDM) is considered as an integrated TOPSIS-AHP (i.e. Technique for Order of Preference by Similarity to Ideal Solution - Analytic Hierarchy Process) with all details of the TOPSIS model applied for evaluation of WWT technologies being found in the study of Sadr et al., 2015. The main advantage of this new approach over the conventional MCMEDM is the pair-wise comparison of criteria. Although previous results matched existing water reuse case studies, the evaluation of criteria by the experts - who have participated in both surveys - was reported problematic due to lack of an appropriate and convenient comparison approach for the evaluation of water reuse criteria. They also indicated that pair-wise comparison of criteria would make the evaluation process less biased and more precise, and ease it, although it would be slightly more time-consuming. The pair-wise comparison was considered for this study as it will help in improving the user's (water reuse experts or stakeholders) satisfaction and in making the IMCMEDM approach more user-friendly. The pair-wise comparison of criteria results in numerical values corresponding to rows (j) and columns (k):

matrix element: $C_{jk}$, where criterion $C_j$ is compared against $C_k$: 
Equation 1

For diagonal elements, where \( j = k \), we have:
\[ C_{jk} = C_{kj} = 1 \]
Equation 2

And:
\[ TW_j = \sum_{k=1}^{n} C_{jk} \]
Equation 3

where: \( TW_j \) denotes total score for the \( j \)-row. To normalize the fuzzy number, the sum of scores of all rows is required:
\[ \text{Sum} = \sum_{j=1}^{n} TW_j = (\text{Sum}_1, \text{Sum}_2, \text{Sum}_3) \]
Equation 4

where: \( \text{Sum}_1, \text{Sum}_2, \) and \( \text{Sum}_3 \) are the three elements of a triangular fuzzy number.

The importance of each criterion based on each expert’s evaluation can be calculated as follows:
\[ W_{aj} = \left( \frac{TW_{1j}^k}{\text{Sum}_1}, \frac{TW_{2j}^k}{\text{Sum}_2}, \frac{TW_{3j}^k}{\text{Sum}_3} \right), \quad a \in \{1, 2, 3\} \]
Equation 5

where: \( a \) and \( k \) denote the order of elements in a triangular fuzzy number and the numbers given by each expert, respectively.

The linguistic variables and their attributed fuzzy sets that are required to rate the WWT technologies under the evaluation criteria are presented in Table 1(a).

The rating of technologies against different criteria and their weights by \( k \) decision makers are computed by Equations 6 and 7, respectively (Chen, 2001, 2000):
\[ \tilde{x}_{ij} = \frac{1}{K} \left[ \tilde{x}_{1ij} + \tilde{x}_{2ij} + \cdots + \tilde{x}_{Kij} \right] = \left( \frac{1}{K} \sum_{p=1}^{K} x_{1ij}^p, \frac{1}{K} \sum_{p=1}^{K} x_{2ij}^p, \frac{1}{K} \sum_{p=1}^{K} x_{3ij}^p \right) \)
Equation 6

\[ \tilde{w}_j = \frac{1}{K} \left[ \tilde{w}_1^j + \tilde{w}_2^j + \cdots + \tilde{w}_K^j \right] = \left( \frac{1}{K} \sum_{p=1}^{K} w_1^p, \frac{1}{K} \sum_{p=1}^{K} w_2^p, \frac{1}{K} \sum_{p=1}^{K} w_3^p \right) = (w_{1j}, w_{2j}, w_{3j}) \]
Equation 7
where: $\tilde{x}_{ij}^k$ is the rating and $\tilde{w}_{ij}^k$ is the weight of the criterion given by the k-expert, who participated in the survey. The defined linguistic variables and the corresponding fuzzy sets for evaluation of the criteria are presented in Table 1(b).

The Fuzzy Decision Matrix (FDM) is then normalised (Equations 8 and 9) with a view to ensuring compatibility between qualitative and quantitative criteria, alleviating the normalisation challenges in the older versions of TOSIS models, and achieving the closed interval of $[0,1]$.

$$R = [\tilde{r}_{ij}]_{m \times n} \quad i = 1, 2, ..., m \quad j = 1, 2, ..., n$$

Equation 8

where: $R$ is the normalised matrix of the fuzzy decision, and $\tilde{r}_{ij}$ is equil to:

$$\tilde{r}_{ij} = \left( \frac{x_{1ij}}{c_{ij}^1}, \frac{x_{2ij}}{c_{ij}^2}, \frac{x_{3ij}}{c_{ij}^3} \right) = (r_{1ij}, r_{2ij}, r_{3ij}) \quad C_j^i = \max_i C_{ij}$$

Equation 9

In this step, the weights are incorporated into the normalized FDM (Equation 10). Each element $(\tilde{v}_{ij})$ is calculated by using Equation 11 (Anagnostopoulos et al., 2008):

$$\tilde{V} = [\tilde{v}_{ij}]_{m \times n} \quad i = 1, 2, ..., m \quad j = 1, 2, ..., n$$

Equation 10

$$\tilde{v}_{ij} = \tilde{r}_{ij} \otimes \tilde{w}_{ij} = (r_{1ij}, r_{2ij}, r_{3ij}) \otimes (w_{1ij}, w_{2ij}, w_{3ij}) = (r_{1ij}w_{1ij}, r_{2ij}w_{2ij}, r_{3ij}w_{3ij}).$$

$$r_{1ij} \geq 0, w_{1ij} \geq 0$$

Equation 11

where: $\otimes$ represents multiplication in a fuzzy environment. It is noteworthy that the weights given (by the experts) to the evaluation criteria very much depend on and are affected by the context and its environmental, social and technical conditions. The weights may also be influenced by water reuse regulations and guidelines implemented in the region of interest.

Once the fuzzy positive-ideal solution ($A^+ = (D_1^+, D_2^+, ..., D_n^+)$) and fuzzy negative-ideal solution ($A^- = (D_1^-, D_2^-, ..., D_n^-)$) are defined, the vertex method is used to calculate the distance $D_i(\ldots)$ of each alternative from $A^+$ and $A^-:

$$D_1^+ = \sum_{j=1}^{n} D(\tilde{v}_{ij}, \tilde{v}_j^+) = \sqrt{\frac{1}{3} \left[ (\tilde{v}_{1ij} - \tilde{v}_j^+)^2 + (\tilde{v}_{2ij} - \tilde{v}_j^+)^2 + (\tilde{v}_{3ij} - \tilde{v}_j^+)^2 \right]}$$

Equation 12

$$D_1^- = \sum_{j=1}^{n} D(\tilde{v}_{ij}, \tilde{v}_j^-) = \sqrt{\frac{1}{3} \left[ (\tilde{v}_{1ij} - \tilde{v}_j^-)^2 + (\tilde{v}_{2ij} - \tilde{v}_j^-)^2 + (\tilde{v}_{3ij} - \tilde{v}_j^-)^2 \right]}$$

Equation 13
where: $\check{v}_j^+ = (\check{v}_{1j}^+, \check{v}_{2j}^+, \check{v}_{3j}^+) = (1,1,1)$ and $\check{v}_j^- = (\check{v}_{1j}^-, \check{v}_{2j}^-, \check{v}_{3j}^-) = (0,0,0)$ when $j = 1, 2, ..., n$.

Finally, the overall performance of all WWT trains (representing their scores and ranks) is calculated by the closeness coefficient ($CC_i$) using Equation 14 (Chen, 2000):

$$CC_i = \frac{D_i^-}{D_i^- + D_i^+} \quad i = 1, 2, ..., m$$

Equation 14

with $CC_i$ ranging from 0 to 1. High value of $CC_i$ indicates better performance of the $i^{th}$ technology, whereas a smaller value points out that the $i^{th}$ solution does not perform well.

In this study, the mathematical model has been incorporated into the IMCMEDM tool. The IMCMEDM is a stand-alone decision support tool with a user-friendly Graphical User Interface (GUI) developed in a MATLAB environment. More information on the GUI is provided in the Supplemental Online Material (SOM).

**Table 1**: Linguistic Variables (LVs) and Fuzzy Sets (FSs): (a) employed for WWTTs rating under each criterion, (b) employed for assigning the weights of the criteria (adapted from Sadr et al., (2015)).

<table>
<thead>
<tr>
<th>LVs and FSs (a) employed for WWTTs rating under each criterion</th>
<th>Linguistic variables</th>
<th>Code</th>
<th>Fuzzy sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very poor</td>
<td>VP</td>
<td>(0.00, 0.00, 0.10)</td>
</tr>
<tr>
<td>2</td>
<td>Poor</td>
<td>P</td>
<td>(0.00, 0.10, 0.30)</td>
</tr>
<tr>
<td>3</td>
<td>Medium poor</td>
<td>MP</td>
<td>(0.10, 0.30, 0.50)</td>
</tr>
<tr>
<td>4</td>
<td>Medium</td>
<td>M</td>
<td>(0.30, 0.50, 0.70)</td>
</tr>
<tr>
<td>5</td>
<td>Medium good</td>
<td>MG</td>
<td>(0.50, 0.70, 0.90)</td>
</tr>
<tr>
<td>6</td>
<td>Good</td>
<td>G</td>
<td>(0.70, 0.90, 1.00)</td>
</tr>
<tr>
<td>7</td>
<td>Very good</td>
<td>VG</td>
<td>(0.90, 1.00, 1.00)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LVs and FSs (b) employed for assigning the weights of the criteria</th>
<th>Linguistic variables</th>
<th>Code</th>
<th>Fuzzy sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Extremely less Important</td>
<td>ELI</td>
<td>(0.00, 0.00, 0.11)</td>
</tr>
<tr>
<td>2</td>
<td>Strongly less important</td>
<td>SLI</td>
<td>(0.00, 0.11, 0.22)</td>
</tr>
<tr>
<td>3</td>
<td>Moderately less important</td>
<td>MLI</td>
<td>(0.11, 0.22, 0.33)</td>
</tr>
<tr>
<td>4</td>
<td>Weakly (Slightly) less important</td>
<td>WLI</td>
<td>(0.22, 0.33, 0.44)</td>
</tr>
<tr>
<td>5</td>
<td>Equally important</td>
<td>EI</td>
<td>(0.33, 0.44, 0.55)</td>
</tr>
<tr>
<td>6</td>
<td>Weakly (Slightly) more important</td>
<td>WMI</td>
<td>(0.44, 0.55, 0.66)</td>
</tr>
<tr>
<td>7</td>
<td>Moderately more important</td>
<td>MMI</td>
<td>(0.55, 0.66, 0.77)</td>
</tr>
<tr>
<td>8</td>
<td>Strongly more important</td>
<td>SMI</td>
<td>(0.66, 0.77, 0.88)</td>
</tr>
<tr>
<td>9</td>
<td>Extremely more important</td>
<td>EMI</td>
<td>(0.77, 0.88, 1.00)</td>
</tr>
</tbody>
</table>

8
2.2 Phase 2: Defining water reuse scenarios

Prior to defining water reuse scenarios, we considered two real case studies of water reuse from different regions with different environmental, social, demographic, legislative and technological conditions. The final ranking of the treatment trains can significantly vary depending on these conditions. Here first, the geographical and environmental situations in each scenario (region) are discussed. We then investigated the water reuse legislation in both cases to ensure that the defined scenarios do not come into conflict with local regulations (especially environmental).

2.2.1 Case study 1: Sao Paulo, Brazil

Sao Paulo Metropolitan Region (SPMR) is located in the east of Brazil (Figure S1 in the SOM). The predominant climate is tropical-wet and it consists of 39 municipalities aggregating approximately 20 million inhabitants, which is 48% of the state population, (SEADE, 2012). Water reuse is becoming increasingly critical in Latin America, especially in large, populous cities with water management having become a significant challenge, mainly due to high rate of urbanisation that is not evenly distributed (Morihama et al., 2011). In SPMR, water resources are traditionally provided by surface water sources (91%), while groundwater sources are fundamental as a complement to the region’s water supply (Coroado, 2012). In the early stages of regional development, increased focus on quantity rather than quality resulted in deterioration in water quality. As the implementation of water recycling and reuse schemes are currently of importance, suitable and reliable WWT technologies should be implemented to ensure promotion and protection of public health and the environment.

2.2.1.1 Water reuse legislation and guidelines in Sao Paulo, Brazil

Although no specific water reuse guidelines have been officially developed in Brazil, there are few general policies related to water reuse; the most relevant one was passed on November 2005 by the National Council of Water Resources, Resolution nº 54. This regulation focuses only on the definitions of permitted water reuse categories and general procedures for management of water reuse schemes; although no quality standards were proposed.

There is a guideline from the Brazilian Association of Technical Standards, NBR 13, 969, which does focus on water re-use applications in a few sections (ABNT, 1997). In particular, Section 6 specifies general orientation for implementing local water reuse schemes and also proposes four classes of non-potable water reuse, according to its intended application. Comparing the local water quality standard in NBR 13,969 with
quality standards in other international guidelines (USEPA, 2012; WHO, 2017, 2006a), this standard can hardly be accepted for any reuse application in urban areas. Due to the growing rate of water consumption and increasing interest in water recycling and reuse, a water reuse scheme was developed by Sabesp in 2002. It enforced SPMR to use treated effluent for public place washing, parks, gardens, and sportive field irrigation, and was regulated by Decree n° 44,128 (Sao Paulo, 2012), which states that the water companies especially water suppliers should be consulted with regard to the standards of the physical, chemical and microbiological properties of reused water (Coroado, 2012). In 2005, the Sao Paulo City Hall mandated a more comprehensive law in the "Municipal Program for Water Conservation and Rational Use in Households and Buildings".

In addition, many industries started to plan the implementation of water reuse schemes by developing their own guidelines proposing specific quality standards. This approach resulted in individual agreements among the reuse water users and suppliers. The most remarkable agreement was the one between the AQUAPOLO Project and the CAPUAVA Industrial Complex, which resulted in a reuse water quality standard that would only be complied if advanced wastewater treatment technologies were applied. In this case the restrictions imposed for the industries, because of fresh water scarcity challenges in the SPMR and by the industries for the water suppliers, driven the decision-making process for the definition of the final wastewater treatment arrangement using advanced technologies.

2.2.1.2 Defining a scenario of water reuse application in Sao Paulo, Brazil

In SPMR, there are a number of water reuse projects and programmes - (e.g., Sabesp, AQUAPOLO). In this study, we focused on the AQUAPOLO Project, which appears to be a suitable one for testing and validating the IMCMEDM approach. AQUAPOLO is one of the largest WWT plants in Latin America where 1 m³ s⁻¹ of effluent is treated by Membrane Bioreactor (MBR) and Reverse Osmosis (RO) units. It is then distributed to the CAPUAVA petrochemical complex in Mauá city (Ambiental, 2011). More information on this case study is provided in the SOM (Table S1). This project aimed to establish sustainable practices of water reuse (Coroado, 2012), and based on the fact that water reuse practices have become critical for Sao Paulo, the following scenario was considered: Scenario 1: WWT through advanced technologies (membrane-assisted) for industrial water reuse, e.g., cooling towers.
2.2.2 Case study 2: Herakleion, Greece

The study focuses on Herakleion, which is the fourth largest city in Greece and is located at the north of Crete. Crete is about 8,336 km² with approximately 600,000 residents (Figure S2 in the SOM). Greece is considered as a water-stressed country (EEA, 2005).

In the early 1990s, total water consumption was reported about 5,500 million m³ y⁻¹, while this amount increased to 7,150 million m³ y⁻¹ in 2000, indicating an increase of 3% each year (EEA, 2005). Furthermore, fresh water resources are unevenly distributed with some regions suffering from water scarcity particularly in summer due to low precipitation and high demand (Tsagarakis et al., 2004). To tackle the problem, the country is compelled to use alternative water resources alongside an appropriate water management methods. To this end, an established framework for community action in the field of water policy was introduced via the implantation of the European Union Water Framework Directive (WFD) stating that for communities of more than 2,000 population equivalent, collection and treatment (up to secondary treatment) of wastewater is required.

2.2.2.1 Water reuse legislation and guidelines in Greece

In 2011, the Greek parliament adopted legislation (354B/2011) to exploit treated wastewater as a renewable resource. Specifically, the legislation refers to the following water reuse purposes (Greek Gazette, 2011): 1) WWT for irrigation including both restricted and unrestricted irrigation, 2) recharge of underground aquifers and reduction in seawater intrusion, 3) urban reuse, and 4) wastewater reuse for industrial activities. According to Bixio et al., (2006), 23 million m³ d⁻¹ of wastewater is reused in Greece, representing around 10% of total WWT plant (WWTP) effluent. Freshwater, currently used for agricultural purposes, can be retained for high-priority applications (Aggelides et al., 2005).

2.2.2.1 Defining a scenario of water reuse application in Herakleion, Greece

The operation of Herakleion Wastewater Treatment Plant (WWTP) started in 1996 and it is going to operate until its environmental terms expire in June 2020. The WWTP, currently serving the municipalities of Herakleion and Gazi, meets the demands of about 200,000 inhabitants. Domestic wastewater is primarily conveyed to the plant through the sewerage system, whilst tanker trucks serve a small portion of the population (7,000 people). It is worth noting that the Herakleion plant is a municipal WWTP and does not treat industrial wastewater (YPEKA, 2012).
The current WWTP includes the following units (EDEYA, 2015): screens (pore size: 9 mm), two units of aerated grit chambers, two Primary Sedimentation Tanks (PST), a selection tank, five chambers and six agitators, two lines of two aerobic-anoxic tanks per line, two Secondary Sedimentation Tanks (SST), and disinfection with NaOCl (15%) in channels at the perimeter of SST, with treated effluent being discharged at sea (Kazos, 2013). Recently, an expansion of the WWTP has been proposed to help meet the demands of an additional 30,000 people. The expansion will be based on membrane technologies, in particular, MBRs are planned to be implemented (Kazos, 2013). The redeveloped WWTP is going to treat 36,000 m³ d⁻¹, corresponding to 194,000 people (EDEYA, 2015). The expected characteristics of effluent after the adaptation are provided in the SOM (Table S2). The following scenario is then defined for reuse of the WWTP effluent in Herakleion: Scenario 2: WWT using membrane technology for unrestricted agricultural irrigation in Herakleion.

2.3 Phase 3: Justification of the evaluation criteria
Depending on the water reuse scenario, the number of criteria and weights of each selected criterion are different. Sweetapple et al., (2014) evaluated five criteria (objectives) in their research, Joksimovic et al., (2006) considered eight criteria, Flores-Alsina et al., (2008) and Sadr et al., (2016) considered nine, and finally Sadr et al., (2015) employed ten criteria. However, regardless of the number of evaluation criteria, it is imperative to consider the following aspects: (1) economic, (2) technical, (3) social and (4) environmental. As this study implemented an improved version of MCMEDM model developed by Sadr et al., 2015, similar evaluation criteria will be considered (See Figure S3, in the SOM).

2.4 Phase 4: Justification of the WWT trains
Each WWT train comprises a number of unit processes, which can be categorised into the four standard stages of treatment: 1) Primary Treatment (PT) 2) Secondary Treatment (ST) 3) Tertiary Treatment (TT) and 4) Disinfection (DI). There are various unit processes to be considered in each stage, therefore, a large number of WWT trains can be formed by different unit processes. Joksimović, (2006) calculated the number of possible WWT technologies for different water reuse purposes, e.g. 190 treatment trains for irrigation re-use and 149 for indirect-potable water re-use. Considering the availability of technologies and feasibility of their installation, operation and maintenance in the targeted regions, ten WWT technologies have been shortlisted for the final evaluation by the water re-use experts in this study (Figure 2).
2.5 Phase 5: Evaluation by water re-use experts

Based on the description and characteristics of the defined scenarios and the proposed mathematical approach of the IMCMEDM, two questionnaires (as part of the IMCMEDM tool) were prepared and distributed to a number of wastewater engineers and water reuse experts (from both the academia and industry) in Brazil and Greece. The participants were selected based on the contexts (scenarios) and their areas of expertise. In this study, similar to many other TOPSIS-based GDM approaches, a number of experts were invited (three in Scenario 1 and four in Scenario 2) and all experts were regarded as equally qualified and competent (Agrawal et al., 2016; Behzadian et al., 2012; Chen, 2001; Jaiswal and Mishra, 2017; Tavana and Hatami-Marbini, 2011; Zyoud et al., 2016).

Expert responses were incorporated into the IMCMEDM tool to build decision-making matrices for different scenarios (Phase 6). Table 2 illustrates the experts' responses (in Scenario 1) for the appraisal of WWT trains against different decision criteria. The colour-coded ratings in Table 2 shows that generally the technology ratings (under each criterion) are similar for all the experts. However, there were few disparities between the given rates as well, for example, the rating of T5 against C8 (land requirement) were different, where Experts 1, 2 and 3 assigned the rates of Good (G), Medium Poor (MP) and Poor (P) to T5 respectively. On the other hand, the pair-wise comparison of the decision criteria were more diverse among the experts as expected (see Tables S3 to
S9, in the SOM). This is due to the fact that each expert generally has different priorities and preferences. Again this is where a powerful GDM, such as the proposed approach, can merge the experts' opinions into one decision matrix and help the decision makers finalise a decision. General responses of the experts for comparison of technologies with respect to each criterion for Scenario 2 are also colour-coded and summarised in the SOM, Table S10.

3 Results and Discussion

3.1 Scenario 1: WWT through advanced technologies (membrane technology) for industrial water reuse, e.g. cooling towers in Sao Paulo, Brazil

As this scenario is defined based on a successful project that is under operation for several years, it is used here to validate the IMCMEDM model/tool. As mentioned in Section 2.1, the ranking system is formed based on $C_i$ using Equation 14, with the option with the highest value being the best technology (Figure 3(a)). For this scenario, T2 ($PT \rightarrow iMBR$ (anaerobic $\rightarrow$ anoxic $\rightarrow$ aerobic $\rightarrow$ MF/UF) $\rightarrow$ DI) and T7 ($PT \rightarrow iMBR$ (anoxic $\rightarrow$ aerobic $\rightarrow$ Microfiltration (MF)/Ultrafiltration (UF) $\rightarrow$ Nanofiltration (NF)/Reverse Osmosis (RO) $\rightarrow$ DI) obtained the top CCs (0.3879 and 0.3835, respectively) and therefore, they are identified as the preferred options. The least preferred technology is T9 with a score of 0.3313.

The sequence of the closeness coefficients represents the main concerns in this scenario observed by the experts in Brazil. Previous studies have reported emergent concerns over the performance of conventional treatment technologies in terms of removing emerging contaminants (Arriaga et al., 2016). The WWT train at AQUAPOLO is comprised of preliminary treatment, PT, MBR, DI and RO. T7, the 2nd best technology, is basically an MBR tailed by NF or RO, followed by DI. It is interesting that RO is occasionally employed, for instance when total dissolved solids (TDS) concentration of the effluent is very high. Considering occasional implementation of RO in AQUAPOLO, T2, the 1st option selected by the IMCMEDM model, is very similar to the wastewater technology configuration in AQUAPOLO.
**Table 2:** The colour-coded fuzzy ratings of the treatment trains (T1 to T10) against different decision criteria (C1 to C10) by three WWT and water reuse experts (E1, E2, and E3) for Scenario 1

<table>
<thead>
<tr>
<th></th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E1</td>
<td>E2</td>
<td>E3</td>
<td>E1</td>
<td>E2</td>
</tr>
<tr>
<td>T1</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>T2</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>T3</td>
<td>VG</td>
<td>VG</td>
<td>VG</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>T4</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>T5</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
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<tr>
<td>T6</td>
<td>G</td>
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<td>G</td>
<td>G</td>
</tr>
<tr>
<td>T7</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>MG</td>
<td>MG</td>
</tr>
<tr>
<td>T8</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>T9</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>T10</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>M</td>
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**Linguistic variables**

<table>
<thead>
<tr>
<th>Code</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>VP</td>
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</tr>
<tr>
<td>P</td>
<td>Poor</td>
</tr>
<tr>
<td>MP</td>
<td>Medium poor</td>
</tr>
<tr>
<td>M</td>
<td>Medium</td>
</tr>
<tr>
<td>MG</td>
<td>Medium good</td>
</tr>
<tr>
<td>G</td>
<td>Good</td>
</tr>
<tr>
<td>VG</td>
<td>Very good</td>
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</tbody>
</table>
Figure 3: Results on Water Reuse Scenario 1 - AQUAPOLO: (a) the IMCMEDM bar chart (b) criteria contribution of various WWT systems.
The result can also be more extensively analysed by the criteria contribution bar chart (Figure 3(b)). The dissimilarity of coloured bars illustrates that the technologies with high CCs generally have high performance under different evaluation criteria. This means that if an alternative obtains high rates (scores) for many or even all evaluation criteria, it is most likely to be among the alternatives with the highest performance and rankings. Figure 3(a) and 3(b) show that T1, T2 and T7 perform well whereas T5, T6, and T9 are shown to be the least preferred technologies. All the preferred alternatives have smaller footprint, which is mainly attributed to the exclusion of sedimentation tanks (ST). T7 is shown to perform well in contaminant removal (C10). In spite of its low contribution in CAPEX (C1), OPEX (C2) and energy consumption (C3), T7 is shown to be the 2nd best solution as it performs well under C4, C5, and C10.

3.2 Scenario 2: WWT using membrane technologies for unrestricted agricultural irrigation in Herakleion, Greece

In this scenario, treatment systems were evaluated against the defined criteria. Figure 4(a) illustrates that T3 and T4, which both are Conventional Activated Sludge Processes (CASP), obtain the highest CCs (0.3594 and 0.3441, respectively). T6 received the lowest score of 0.1843. It can be inferred that the experts believe that CASP are reliable and effective enough in terms of contaminant removal for non-potable water reuse purposes with similar WWT trains having already been suggested in previous studies and projects (Norton-Brandão et al., 2013; Judd and Judd, 2011; Melin et al., 2006). Figure 4(b) shows that T3 and T4 are the preferred technologies, whilst T6 is the least preferred. T3 and T4 perform well with respect to C1, C2, and C3. T5, T7, T9 and T10 are considered as technologies with high OPEX; this is mainly associated with high energy consumption of NF/RO. These technologies are also characterised by large footprint and high investment (capital) expenditure.

T2 consists of fewer treatment unit processes (compared to the other WWT technologies), which resulted in a smaller footprint. It is noteworthy that, although T5 does not perform well under C1 and C2, it does show high performance within the rest of the evaluation criteria and therefore, it is among the technologies with the best performance. T5, a technology leading to very high effluent quality, attained high score reflecting the water quality concerns that are associated with human health and environmental issues. Hence, T5 should be considered in locations with relatively high environmental awareness and willingness to pay. The results of this scenario pointed
that participants from Greece do not consider MBR as their 1st option, in particular, when CASP are available.

3.3 Sensitivity analysis

It can be seen in the results provided in Sections 3.1 and 3.2 that generally the closeness coefficients were relatively lower in Scenario 1 compared to those in Scenario 2. This shows that the performances of the WWT trains are generally closer to that of the ideal solution (defined based on the TOPSIS approach) in Scenario 2. The closeness coefficient values of each alternative very much depend on the experts’ preference and priorities, which are defined based on both the context and the experts’ opinions and interests. To this end, in order to explore the sensitivity of the values of closeness coefficient (i.e. the distance of each alternative from the ideal solution with respect to different criteria) to changes in the experts' weightings, a two-at-a-time sensitivity analysis was performed in both Scenarios 1 and 2. The sensitivity analysis was focused on the weights of the evaluation criteria (namely: C1: capital cost; C2: O & M Cost; C3: energy consumption; C4: environmental Impact; C5: community acceptance; C6: adaptability; C7: ease of construction and deployment; C8: land requirement; C9: level of complexity and C10: water quality). The overall weight of each criterion were changed by ±20% in each scenario (see Figure 5).

Figure 5 and Figure S4 (in the SOM) shows that the closeness coefficients in Scenario 1 are more sensitive to changes in criteria weightings compared to those in Scenario 2. The highest sensitivity in Scenario 1 can be seen for T8 (PT + Chemically Enhanced Primary Treatment (CEPT) + MF/UF + DI), which was among the least preferred technologies in this scenario; this was observed when C5 (i.e. community acceptance) was changed (see Figures S12 and S13, in the SOM). This is due to the fact that all the experts rated this treatment train ‘Medium’, which is generally lower than the rates of other technologies with respect to this criteria (see Table 2). The least sensitivity in Scenario 1 was seen in the value of T2’s closeness coefficient (+0.050 and -0.034), whilst the highest was observed in that of T8 (+0.248 and -0.115). In Scenario 2, T3 (+0.250 and -0.215) and T6 (+0.189 and -0.150), respectively, showed the highest sensitivity to the changes of criteria weights. In this scenario, closeness coefficients were significantly impacted by the variation in C1; where sensitivity to the (simultaneous) alteration of C1 - C6, C1 – C7 and C1 – C2 presented the highest changes among the others, whereas, in Scenario 1, alterations of C10 resulted the highest variations in the result; for example, a simultaneous increase in the weights of C10 and C6 (20% each) increased closeness coefficients by 0.072 (on average).
The variations and differences shown in the sensitivity analysis of Scenario 1 and Scenario 2 support the fact that the results of such GDM tools, to a certain extent, depend on the experts’ opinions and preferences. Therefore, the process of selecting experts is of high importance as to determine how suitable or relevant their expertise is; this introduces a new approach in which a weight is assigned to each expert (based on their knowledge and experience or some other factors) in the group decision making process (Pang et al., 2017; Yang et al., 2017; Yue, 2012). However, this is out of the scope of the current study, but would be a good addition for future research. In this study, similar to several other GDM approaches (Agrawal et al., 2016; Behzadian et al., 2012; Kalbar et al., 2013; Ren and Liang, 2017), all experts were regarded as equally important and pertinent. The design of the survey (questionnaire) or the tool (which contains the survey) would have meaningful impacts on the results of the study (Bowling, 2005; Jonker and Kosse, 2009; Nardi, 2018).
Figure 4: Results on Water Reuse Scenario 2 - Herakleion: (a) the IMCMEDM bar chart (b) criteria contribution of various WWT systems
4 Conclusions and Implications

Modifications and improvements were made to the MCMEDM model that has been previously presented by Sadr et al. in 2015. The new improved model (IMCMEDM) was incorporated into a decision support tool with a user-friendly GUI. The tool, which integrates TOPSIS with AHP, provided a ranking system for comparing WWT trains in terms of their performance. Two scenarios of water reuse and WWT in the contexts of Brazil and Greece were proposed with respect to ten criteria in order to select reliable options within a set of ten pre-shortlisted WWT trains. The decision-making process was
first conducted by the development and distribution of two questionnaires to a number of
participants from different areas of expertise from both academia and the industry. Then,
the collected data formed the decision matrices used in the IMCMEDM tool. Hence, the
tool provides a streamlined and robust framework in order to guide decision makers in
the decision process. Notably, the contributions of designated experts in the field is
formalised and thus standardised. This fact renders the decision process significantly
less vulnerable to personal bias as long as an appropriate (or a manageable) number of
experts is involved. Furthermore, the user-friendly GUI levels an important barrier for
implementation by policy decision makers. A first scenario regarding water reuse in Sao
Paulo, Brazil, was proposed based on an existing industrial water reuse project to
validate the tool. The results of this scenario coincided with the project in Sao Paulo.
Next, a second scenario that focussed on water reuse applications in Greece was
investigated and it showed that CASPs are still more prevalent than MBRs in this region.
This represents a clear evidence that technology preference very much depends upon
the context, and/or pertains to the socio-technical background of the decision makers. It
thus highlights the importance of consulting with local experts in order to cover the social
and regulatory context appropriately. It also confirms the fact that selecting the panel of
decision makers is an important process.
In both scenarios, the participants assigned the highest weights for capital cost,
operation and maintenance cost, and energy consumption. Although we observed that
criteria weighing of the above criteria were rather independent from the two presented
scenarios, we expect that criteria ranking depends on the location in general (i.e. footprint
is more restricting in urban context). Hence, future work will extend the scenario settings
to rural areas in order to account for that. Future work will concentrate on further
application of this flexible tool to different sets of evaluation criteria, WWT technologies
and contexts.
In this study, technologies were relatively assessed with respect to different criteria (e.g.
CAPEX, OPEX and energy consumption). Future studies can incorporate the results of
more-in-depth cost assessment and life cycle assessment into this tool. Such attempts
would give decision makers more confidence in the results of the tool. Having
investigated the process of decision making and technology selection for water reuse
schemes in different contexts with distinct regulations and different geographical,
environmental, economic and demographic situations, the outcomes of this piece of
research would contribute substantively to the application of WWT technologies
(especially membrane assisted technologies) for different water reuse scenarios.
Acknowledgements

The authors would like to acknowledge all the water reuse experts from Greece and Brazil who participated in the surveys. The authors are particularly thankful to The Environmental Odebrecht (Brazil) for providing data to the AQUAPOLO Project.

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