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Shaher Zyoud

# Multi-criteria decision making techniques for water loss management in water supply networks of developing countries

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**TECHNISCHE UNIVERSITÄT GRAZ**

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**76**

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# Multi-criteria decision making techniques for water loss management in water supply networks of developing countries

Doctoral Thesis

Institute of Urban Water Management and Landscape Water Engineering
Technische Universität Graz
(Graz University of Technology)

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# Abstract

Water utilities in most of the developing countries follow complex operation techniques for the distribution of available amounts of water, e.g. intermittent water supply module. This is driven by different factors such as: increasing water demands in parallel with water scarcity conditions and technical and economic deficiencies. This approach, to a large extent, is counterproductive to the objectives of water supply networks (WSNs) and has numerous associated failures like: inequitable distribution of water to all consumers, risks on public health, increasing the rates of assets deterioration or the high rates of bursts as a result of pressure fluctuations. One of the major promising approaches toward mitigation of the previously mentioned deficiencies is the promotion of water loss management practices.

Even though water loss is a worldwide issue, it is more acute in case of the developing countries. It is estimated, according to a World Bank study, that about 55% of the total global non-revenue water (NRW) by volume occurs in the developing countries. Moreover, as it is widely reported in the literature, a substantial work in the developed countries has been devoted to reduce the rates of NRW in their WSNs with an aim of improving the performance of their systems, an insufficient work has been done in the same context in the developing world. Accordingly, in parallel with seeing the reduction of water losses to economic levels as a key to sustainable water resources management, the high opportunity costs of water losses and the potential of investment in the recovered water to fill the gaps between available supplies and required demands can help in improving the supply services in the developing countries. Moreover, it promotes the gradual switching from intermittent supply to continuous supply services.

There are numerous challenges in managing water losses, manifested in a variety of alternatives, alternatives' complexities and differences in costs and impacts and conflicting objectives and interests of different stakeholders. The integration of multi criteria decision making (MCDM) techniques to solve complex decision making problems in water loss management is vital and helpful. MCDM approaches are being emphasized among the developed world in the context of water resources management, and still in their infancy stage in most of the developing world and the related techniques are typically less applied.

Accordingly, the major aims of this research were to:
1- Introduce the principles and applications of MCDM techniques in water loss management practices in the developing countries to: improve the planning policies of water utilities, reach a better control over water losses based on consensus and transparent decisions, increase the efficiency of water utilities and improve the water supply services.
2- Develop an efficient decision support framework to manage water losses by:
- developing a multi criteria decision making framework with the purpose of selecting the most appropriate strategies to reduce water losses in intermittent water supply systems and,
- developing a framework to identify the zones within WSNs that have high priority in terms of water losses with an aim of applying the selected best strategy over zones with high criticality of water losses (through gradual improvements and long term planning).
3- Demonstrate the proof-of-concept of the developed frameworks by applying them to real–world case studies.

The proposed methodology was initiated by developing a hierarchical structure of the decision problem to identify the key alternatives among a set of alternatives that have been proposed to manage water losses in WSNs of the developing countries. This framework takes into account the sustainability dimensions of the decision problem, multi objective evaluation criteria and the concerns of different stakeholders who have interests in this filed. The most influential actors in the water sector of Palestine have been identified and were involved in the consultations about

the decision problem structure and its components and engaged in the evaluation process. This was in parallel with identifying the case study, Nablus Water Distribution System (NWDS)-Nablus city-Palestine, with an aim to proof the developed concepts and methodologies.

One of extensively used MCDM techniques, precisely the analytic hierarchy process (AHP), was employed first to prioritize the proposed water loss management alternatives. To manage the inherent uncertainties in the decision making process, fuzzy set theory has been incorporated with AHP in a later work. This followed by a comparative analysis between the outcomes of the two approaches. An integrated methodology of Fuzzy AHP and Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (Fuzzy TOPSIS) was proposed in the same previous context as it is efficient in terms of reducing the computational complexity (reported in the previous approaches), agility in the decision process and modeling of uncertainty. The outcomes of the previously applied techniques indicate that pressure management and control strategy was the most prevalent one. Its dominance was highly connected to the local and boundary conditions of the case study. There was a large agreement between most of the applied MCDM techniques towards nomination and ranking of the best alternatives to manage water losses. The non-significant difference between the different MCDM techniques in terms of ranking alternatives, particularly for the most and least preferred alternatives, was an indicator for the robustness of the developed water loss management decision making framework. This indicates that the structuring of the decision problem was in a comprehensive and clear way which facilitated the duty of decision makers (DMs) to incorporate their evaluations.

To help water utilities in the developing countries to adopt gradual improvement plans for applying the optimum strategies of managing water losses, there is a need to develop diagnostic tools to understand the conditions of different zones within WSNs and their criticality in terms of water losses and the associated environmental and social consequences. This is motivated by the fact that most water utilities in the developing countries have insufficient financial resources and operational constraints such as the complexity and the extent of WSNs to implement the optimum strategies over the whole systems once a time. In this context, a hybrid framework of Fuzzy AHP, fuzzy synthetic evaluation (FSE) and ordered weighted averaging (OWA) operator for evaluation of a water loss risk index (WLRI) has been proposed and applied over the case study. The WLRI is an index that allows to incorporate the potential of occurrence of water losses in WSNs as a result of different influential factors and the consequences, and can be defined in an interval from 0% to 100%. The framework was initiated by developing a hierarchy structure which involves the most important factors that affect water losses in WSNs and the possible consequences in terms of social and environmental impacts. The Fuzzy AHP was used to derive the relative importance of elements of structure (e.g., the priority weights of the factors that contribute to water losses and their relevance categories) by the aid of a group of experts. The FSE was employed to synthesize the contribution of different factors towards the WLRI of each pipe within a zone, while the OWA operator was used to produce the overall value of WLRI in the tested zones. Scenario analysis and Mont Carlo simulation analysis were employed to acquire a better understanding of the impact of uncertainty in the inputs of the WLRI framework elements on the outcomes.

The developed framework was able to prioritize, rank and categorize a set of selected zones in the case study according to their criticality in terms of water losses. There were small changes in the ranking of zones as a result of applying the scenario analysis with regard to the original outcomes of applying the developed methodology. This scenario analysis was related to exchanging the weight of each main category in the structure with the weight of another main category at a time and by assigning equal weights to all main categories. It was followed by evaluating the WLRI in the tested zones in association with each condition in the scenario analysis and analyzing the changes in ranking of zones. The results of Monte Carlo simulation analysis showed also stability in the ranking based on the associated WLRI values. A correlation of around 0.8 was achieved between the resulted WLRI values of the selected zones and the total water losses for the selected zones based on water balance calculations. This indicates the reliability of the developed framework in evaluating the criticality of zones in terms of water losses. Furthermore, it indicates the potential of applying the developed framework to evaluate the other zones within the examined case study without large investments (i.e. special arrangements to perform the data collection campaigns such as the isolation of the targeted zones and supplying water in a continuous module, and the need for large operational staff).

The outcomes of the proposed methodologies assumed that the introduced MCDM techniques are useful for water utilities in terms of realizing a better understanding and assessment of components of water loss management strategies. It encourages group decision making approaches in principle and in practice with the aim to achieve consensus and concrete actions towards critical issues in the water loss management field. The incorporation of such a MCDM framework in the planning policies of water utilities in the developing countries will be useful for water loss management. This is manifested by its capability to work with limited, and/or lack of quantitative data, which is prevalent in most developing countries. The involving of additional DMs and stakeholders with different backgrounds in the evaluation process is of interest. For the framework that aims to identify the zones according to the associated WLRI, the incorporation of additional factors that affect water losses in WSNs can improve the reliability of the outcomes and depend primarily on the availability of data.

The developed methodologies have been applied and tested for their validity at a WSN in Palestine, which represents a typical developing country water system, and have the potential to be applied to WSNs in other developing countries. This thesis will be of interest for policy makers, water utilities and researchers who have concerns in the field of water loss management, and provides a source of tools and methodologies with potential to address the different challenges associated with water loss management practices, essentially in the developing countries.

**Keywords:** Water loss management, Water supply networks, developing countries, intermittent supply, multi-criteria decision making, Analytic hierarchy process, Fuzzy set theory, Fuzzy synthetic evaluation, Technique for order of preference by similarity to ideal solution, Ordered weighted averaging operator, Sensitivity analysis, uncertainty, Monte Carlo simulation analysis.

# Contents

## List of Abbreviations

| | |
|---|---|
| AHP | Analytical hierarchical process |
| CBR | Case-Based Reasoning |
| $CC_i$ | Closeness coefficient |
| *CI* | Consistency index |
| CI | Cast iron |
| CP | Compromise programming |
| *CR* | Consistency ratio |
| DEA | Data Envelopment Analysis |
| DM | Decision Making |
| DMs | Decision makers |
| ELECTRE | Elimination and Choice Expressing Reality |
| FNIS, $A^-$ | Fuzzy Negative Ideal Solution |
| FPIS, $A^+$ | Fuzzy Positive Ideal Solution |
| FSE | Fuzzy synthetic evaluation |
| Fuzzy AHP | Fuzzy analytic hierarchy process |
| GIS | Geographic information system |
| GMM | Geometric mean method |
| GP | Goal Programming |
| HDPE | High density polyethylene |
| ILI | Infrastructure leakage index |
| IWA | International Water Association |
| MAUT | Multi-attribute utility theory |
| MAVT | Multi-attribute value theory |
| MCDM | Multi-criteria decision making |
| MNF | Minimum night flow |
| MODM | Multi-objective decision making |
| NRW | Non-revenue water |
| NWDS | Nablus water distribution system |
| OVGWA | Ordered visibility graph weighted averaging |
| OWA | Ordered weighted averaging operator |
| OWALD | Ordered weighted averaging operator based on Laplace distribution |
| PHG | Palestinian Hydrology Group |
| PROMETHEE | Preference Ranking Organization and Method for Enrichment Evaluation |
| PVC | Polyvinylchloride |
| PWA | Palestinian Water Authority |
| *R* | Spearman Correlation Coefficient |
| *RI* | Random consistency index |
| RMSE | Root mean square error |
| SAW | Simple additive weighting |
| SMART | Simple multi attribute rating technique |
| TFNs | Triangle fuzzy numbers |
| TOPSIS | Technique for order of preference by similarity to ideal solution |
| WAMM | Weighted arithmetic mean method |
| WDNs | Water distribution networks |
| WLRI | Water loss risk index |
| WQF | Water quality failure |
| WSNs | Water supply networks |
| WSSD | Water supply and sanitation department |

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# 1 Introduction[1]

## 1.1 Background

Water security is amongst the basic human rights which guarantees an access to enough safe drinking water at an affordable costs (WHO 2012). This issue has attracted much attention during the last periods in association with growing water scarcity which is increasingly imposing adverse influences on the objectives of human well-beings (Malekian *et al.* 2017). Vorosmarty *et al.* (2010) found in their study, which was concerned with identifying the global threats to human water security that nearly 80% of total world's population is under high levels of threats to their water security. For wealthy nations, the huge investments in water technologies enable these countries to stabilize the stressor levels without handling the inherent causes, while the deprived countries will continue to be vulnerable to these threats (Vorosmarty *et al.* 2010). The climatic changes, finite water supplies and rising water demands are all threats to the availability of water resources for human consumption and other activities (Vörösmarty *et al.* 2000). Due to the rapid growing of population, agriculture, industrialization, energy production and domestic uses, water demand is continuing to grow up (Srinivasan *et al.* 2013).

The lack of clean and fresh waters causes many problems worldwide. There is 1.2 billion people worldwide without access to safe drinking water, the number of people who don't have proper sanitation is estimated at about 2.6 billion, millions of people are dying annually from water-related diseases transmitted through insecure waters or excreta of humans, and among them there is 3900 children die a day (Montgomery & Elimelech 2007). In the coming decades, it is expected for problems of water to grow even much worse, and the water scarcity will occur globally without even excluding water-rich regions (Shannon *et al.* 2008). The water resources shortage in association with the environmental damages impose constraints on the social and economic developments and cause threats to human health and generate ecological risks (Foley *et al.* 2011). The uncertainty in water resources future conditions necessitates long-term water resources management plans which have adequate capacities to offer alternative management choices (Milly *et al.* 2008; Hassanzadeh *et al.* 2016). Furthermore, to realize the sustainability of water resources, it is required to expand the common water resources management models far beyond the economic extent to involve socially valued ecosystem services (Poff *et al.* 2015).

In the context of water security, both of developed and developing nations are facing distinct but overlapping challenges (Grant *et al.* 2012). In case of developed nations, their existing water supply infrastructures require reengineering with an aim of sustaining the high living standards and in the meantime diminishing their environmental footprint and reviving the biodiversity, while in case of developing nations, there is a need to affordable infrastructures with aims of satisfying their people's needs of water and preserving the aquatic ecosystems (Vorosmarty *et al.* 2010). To meet these challenges, there is a need to balance the delivering of new water sources and the using of water in a more productive way (Grant *et al.* 2012). As mentioned previously, risks to water security emerge mainly due to water scarcity (Falkenmark 2013) which seems to be as a serious issue to socioeconomic developments (Kotir *et al.* 2016). In fundamental way, water scarcity can be break down into two forms: the first one is due to water shortage, which refers to low water availability where large number of people is relied on limited water resources and can be perceived as population–driven water scarcity, while the second one is related to water stress

[1] Parts of this chapter have been published in (Zyoud *et al.* 2016a; Zyoud *et al.* 2016b; Zyoud & Fuchs-Hanusch 2017a; Zyoud & Fuchs-Hanusch 2017b).

which is attributed to the high levels of water use in relative to available waters and can be perceived as demand-driven water scarcity (Kummu *et al.* 2016).

At urban water utilities level, the main two challenges are: the reduction of used energy and the reduction of water losses (Gama *et al.* 2015). The management of water losses is considered as a major issue in the sustainability of these systems and in promoting the effective utilization of water as a precious natural resource (Loureiro *et al.* 2014). Attention towards efficient control and management of water losses from water supply networks (WSNs) has been growing recently (Lambert 2002). This is motivated by numerous factors such as: water losses represent the most relevant indicator of the inefficiency of WSNs (Vilanova *et al.* 2015); the large amounts of water losses attributable to leaks in WSNs which could be as much as 50% of the input to the systems (Puust *et al.* 2010; Leu & Bui 2016); the associated energy waste and revenue losses (Perelman *et al.* 2015; Shafiee *et al.* 2016) and increasing of domestic and industrial water demands due to population growth, urbanization and continuing industrialization which in turn putting great pressure on the available water resources (Dong *et al.* 2016).

## 1.2 Water supply services in developing countries

Water supply and distribution services in developing countries have limited resources to help in their expansion and restoration added to the problem of water shortage (de Almeida-Filho *et al.* 2016). Accordingly, water supply systems in developing countries are unable to supply water to all consumers simultaneously and one of the most practical methods, which is most prevalent in developing countries and used to counteract the water scarcity and shortage is the intermittent water supply (Bozorg-Haddad *et al.* 2016). The intermittent water system can be defined as a water supply system that provides its service of supplying water to consumers for a period of time mostly less than 24 hours per day or few days per week. Currently, intermittent water supply is the trend by which millions of people worldwide received their needs of water or have access to water (Ilaya-Ayza *et al.* 2017). There are at least 300 million people in the world who are served by water supplies which are available for less than 12 hours per day, and the majority of them in sub-Saharan Africa and South Asia (Kumpel & Nelson 2016). One of the major aspects of intermittent water supply systems is the use of private roof/ground storage tanks by customers with an aim of reducing their vulnerability to this type of supply services (De Marchis et al. 2010).

This scheme of operation is counterproductive to the objectives of WSNs which should guarantee a service to consumers characterized by enough quantity and good quality as in the case of continuous water supply service. The continuous supply is the best indicator of good water supply service in terms of water quality, quantity, price, reliability and convenience (McIntosh 2003). This type of water supply represents the ideal operating conditions in which, the input to the network (Klingel & Nestmann 2014) and the hydraulic capacities of the system are sufficient to meet water demands by the consumers. The first portion has to be achievable on the basis of availability of water resources (the system is continuously full), while for the second, the demand by the end users should be independent of the system pressure, which means that the water supply network has sufficient operating pressure (under positive pressure) to fulfill any required demands in time and space (Nyende-Byakika *et al.* 2013). The previous requirements should be accompanied by management plans of water systems on sustainable basis since the sustainability and efficiency of water supply systems depend mainly upon the standards of service delivery at the supplier end and the revenue generation at the consumer end (Hastak et al. 2016).

Continuous water supply systems are common in developed countries where the consumers receive water at full pressure 24 hours a day, 7 days a week. The availability of water from the source and the availability of the means of conveyance and the adequate facilities for distribution guarantee the delivery and supply of water in continuous manner (Abu-Madi & Trifunovic 2013).

While the intermittent supply is very common in developing countries, it is footprint began expanding in developed countries in a little pace (McIntosh 2003). In its origin, it is a consequence and is not a planned tactic, and its usage is governed by inaccessibility to other management plans that have the potential to eliminate the risks of water scarcity, and/or other deficiencies. As previously explained, the main driving force behind the intensive use of this technique in developing countries is the scarcity of water resources and technical and economic deficiencies. The rapid dramatic changes at global level which comprise remarkable shift in urbanization, climate changes, and population growth apply unfavorable stress on already scarce water resources and on existing water supply systems mainly in developing countries which have restricted financial resources. This strategy brings negative consequences in association with its application as shown in details in Figure 1 below. The following section explains in details the main causes of this type of water supply services.

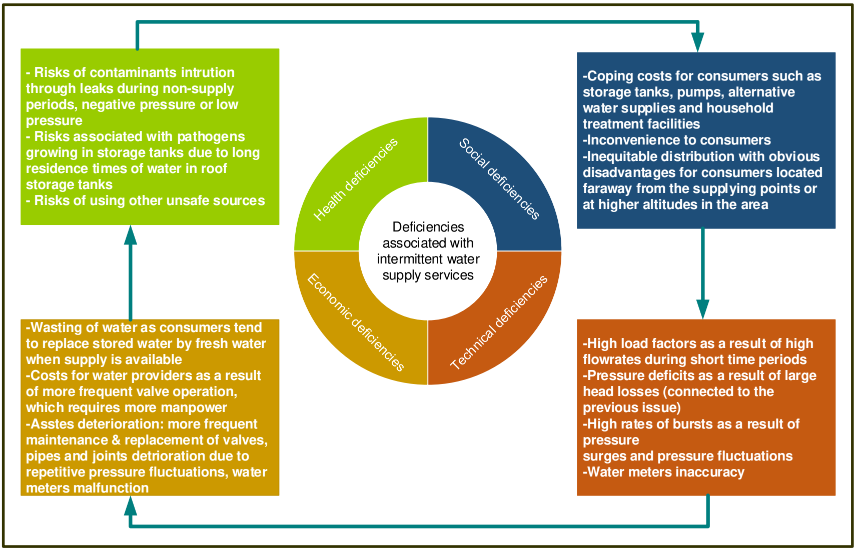



**Figure 1.** Major deficiencies associated with intermittent water supply services.

## 1.2.1 Major causes of intermittent water supply

### 1.2.1.1 Water scarcity–physical scarcity

Water scarcity is a serious environmental problem (Navarro-Ortega *et al.* 2015) related to unavailability of sufficient quantities at the source to meet the required demands and considered the most sophisticated issue to deal with in water supply management (Totsuka *et al.* 2004). It could be an output of natural causes such as aridity and drought, human activities such as desertification and water shortage due to overexploitation of groundwater and surface waters, or a result from interaction of both (Pereira *et al.* 2009). The rapid increase of water demands associated mainly with population growth (Spiliotis *et al.* 2015), urbanization and socioeconomic developments (Liu *et al.* 2016) are major contributions to the low availability of water, and may be further aggravated the water scarcity conditions in the future.

Limitations imposed in developing new water resources in some regions, interregional and international conflicts (Sofroniou & Bishop 2014) contribute to water scarcity conditions. As a result, water utilities are enforced to introduce the discontinuous service (intermittent scheme), and to ration the available amounts of water. This scheme is applicable in solving water scarcity in short term (Fontanazza *et al.* 2007) and can be classified under demand management measures which offer a more efficient use of limited supplies (Vairavamoorthy *et al.* 2008). The alleviation of water scarcity issues could comprise, in addition to the demand management, water reuse, improving irrigation efficiency, energy-water linkages, and transboundary water management (Scott *et al.* 2003).

#### 1.2.1.2 Economic deficiencies-economic scarcity

Economic deficiencies arise mainly in cases where water utilities are not able to develop new water resources and water infrastructure due to financial deficiencies and/or incapable planning strategies. The failure in increasing the capacity of the water distribution infrastructure and the water resources to keep up on pace with the growing demands associated with the population growth will bring water supply disruption and inequitable distribution of water resources into view (Pereira *et al.* 2009). The problem initiates by failing to continuously supply water to all consumers because the existing hydraulic capacity of the system has been exhausted. Later on, the desired demands are not only overreaching the capacity of the system, but also exceeding the potency of the water source to fulfill the desired demands (Totsuka *et al.* 2004). An additional and planned investment in the water sector could play a transformative role in alleviating the effects of economic water scarcity.

#### 1.2.1.3 Technical deficiencies

The failure to take full knowledge about the systems and their future needs, in terms of planning and addressing the overarching systems concepts (Klingel 2012), to maintain the stability and the functionality of the complete system is a primary cause of technical deficiencies. This results for example in the extension of water distribution networks beyond their hydraulic capacity in response to the population growth (McIntosh 2003). The mismanagement practices in setting up a comprehensive system of complete and accurate metering and deficiencies in the systems of charging and collection at sufficient tariff are technical deficiencies which contribute to intermittent supply services (McIntosh 2003). Furthermore, the high rates of non-revenue water (NRW) that emanate from leakage, illegal connections and other components of water losses, wastage of water and poor operation and maintenance practices (Totsuka *et al.* 2004) are additional causes which exacerbate the technical deficiencies in water distribution networks.

There are cases where all previously mentioned deficiencies could be synchronized with each other as in the case of Palestine, where the Palestinians don’t have full sovereignty over their water resources (Zahra 2001; Shuval & Dweik 2007; Abu-Madi 2009). In Palestine, the high rates of NRW, poor design, increasing demands, variances in tariff rates and scarce financial resources are dominant deficits (Abu-Madi & Trifunovic 2013). While in other cases as in Kathmandu, India, the technical deficiencies are prevalence (McIntosh 2003).

### 1.2.2 Management approaches of intermittent water supply systems

There are two principal approaches in this context (Myers 2003; Totsuka *et al.* 2004; Klingel & Nestmann 2014): the first approach has diagnosed the intermittent scheme as a case of failure in the water supply services which should be addressed and tackled by all feasible means as a matter of necessity and urgency, and not as a matter of choice. This approach emphasizes the need to switch from intermittent to continuous supply until the full pressure “24-7” service is restored (World Bank 2003). While the second approach deals with the intermittent supply as an accomplished fact and should adapt with this situation. The supporters of this approach call for developing design tools, guidelines and appropriate technologies with a potential to eliminate the adverse consequences of intermittent supply.

#### 1.2.2.1 From intermittent water supply to continuous supply

As mentioned previously, this approach emphasizes the necessity to correct the misconception of considering the intermittent supply service as acceptable norm. This misconception may stem from the unawareness of the costs and risks associated with the intermittent service (McIntosh 2003). This approach also is looking at the measures to make improvements in the functions of the intermittent supply by developing planning and design tools to be coincide with the nature of the intermittent service as interim measures (Klingel & Nestmann 2014). It is hard to rely on these interim measures as substantial options to the continuous service which is a sustainable, technically sound and secure approach (Kumar 1998; McIntosh 2003; Myers 2003; Dahasahasra 2007; Klingel & Nestmann 2014).

#### 1.2.2.2 Modeling, design and optimization techniques

This approach emphasizes the need to develop appropriate design tools and operation techniques for intermittent systems. In principle, these tools and techniques must rely on rules to be completely distinct from those followed in the case of continuous supply (Totsuka *et al.* 2004). Developing appropriate leak detection methods and proper valve selection to be compatible with flow features in intermittent supply are also required (Totsuka *et al.* 2004). Most of the developed approaches in this regard are devoted to understanding and analyzing the hydraulic behavior of the intermittent supply systems, analyzing the inequality (De Marchis *et al.* 2011) and developing mathematical modelling tools for intermittent supply systems (Vairavamoorthy *et al.* 2001; Totsuka *et al.* 2004) .

## 1.3 Water losses management

Water losses from water distribution networks (WDNs) are major challenges that water utilities are facing worldwide (Mutikanga *et al.* 2013). They are considered as the most relevant index of inefficiency of WDNs (Vilanova *et al.* 2015) as they affect the technical stability and operational age of WDNs, and the quality of water and water services (AL-Washali *et al.* 2016). At economic scale, they have primary effects as they boost the operational costs and entail huge investments in addition to significantly reducing the water utilities revenues when they exceed their commercial or economic levels (AL-Washali *et al.* 2016). The impacts of water losses reduction are beyond the avoiding of losses as a quantity of water, they have to be reassessed in a broader objective which includes the environmental protection (Pillot *et al.* 2016). As the reduction of water losses will reduce the water abstracted, it contributes in reducing the environmental impacts resulted in association with water production (i.e. the requirement for abstraction, treatment and supply of water) (Pillot *et al.* 2016). The associated advantages produced from the exploitation in recovered water in alleviate the shortage of water and the realization of the high opportunity costs of water losses are the core of all initiatives in the context of water losses management.

At global levels, there is an amount much more than 48 billion $m^3$/year that is wasted as non-revenue water, and out of this amount about 66% is wasted as real losses (Kingdom *et al.* 2006; Loureiro *et al.* 2015). The cost of global water losses is estimated at about US $ 14 billion/year, and the average daily leakage from WDNs, as in 2006 estimations, has a potential to render the water supply service for more than 200 million people across the world (Kingdom *et al.* 2006). In developing countries which are encountering difficulties to fulfill the required demands, the non-revenue water (NRW) for the most of them is more than 50% (Kadu & Dighade 2015). In light of growing stresses on the available water resources, the reduction of water losses to economic levels is being more wanted and it is perceived as a key factor in sustainable water management, the next challenge for the mankind (Grit *et al.* 2015; van den Berg 2015). Even though water loss is a worldwide issue, it is more acute in case of developing countries which are experiencing insufficient financial means, are deficient in well-trained staff in this field, shortage in required advanced technologies to detect, locate and fix the leaks in WDNs, and the absence of well-structured public awareness programs in this regard (Al-Omari 2013).

Water losses are categorized into two primary components: real losses (i.e. physical losses which are attributed to leaky pipes whether they are transmission, distribution and/or service connections, bursts, leakages and overflows from storage tanks), and apparent losses which are not lost in physical manner as they are used but not paid for (i.e. commercial losses which are attributed to illegal water consumption, under registration of customers' water meters and data handling mistakes) (Wu *et al.* 2011). The summation of water losses and unbilled authorized consumption (i.e. the amounts used in legal form for public services and not paid for) represents the NRW rate. Figure 2 displays the International Water Association (IWA) standard water balance and its components which is based on the best practices from many countries and introduced by IWA Task Force on Water Losses and Performance Indicators (Farley & Trow 2003).

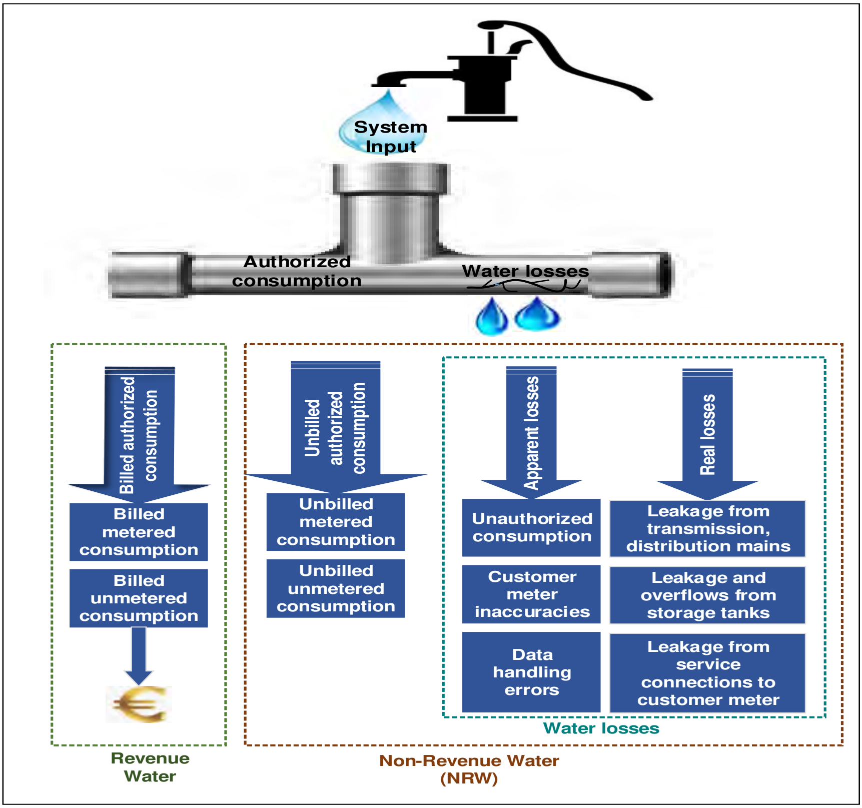



**Figure 2.** IWA best practice standard water balance (adapted from (Farley & Trow 2003)).

## 1.3.1 Characteristics of water losses management process

Many different methods and tools have been evolved to manage water losses in WDNs. These tools are varying in terms of level of complexity and ranging from soft management tools (i.e. performance indicators and benchmarking techniques) to extremely advanced methods (i.e. optimization techniques based on evolutionary and genetic algorithms). The benchmarking techniques are used to improve the performance by comparing the performance indicators of one's business with the best practices in the same context. For water loss management, the most used indicators in benchmarking are those developed by the IWA such as NRW indicator and infrastructure leakage index (ILI) (Alegre *et al.* 2006). The optimization techniques in the field of water loss management include the development of optimization methods for leak detection, optimization of pressure in WDNs and optimization of work of pumps (Mutikanga *et al.* 2013).

Finally, the multi-criteria decision making (MCDM) methods as systematic and transparent approaches have high potential in producing well-structured decisions in this field. They are used by several researchers as decision support tools in water loss management (Mutikanga *et al.* 2011; Fontana & Morais 2013; Morais *et al.* 2014).

The typical integrated real losses management model is shown in Figure 3 below which includes four major activities. The implementation of these four activities to an acceptable level can control the increase in bursts and leaks in WDNs. For the management of apparent losses, which is still in infancy in comparison to real losses management activities (AWWA 2003), the Water Loss Task Force of IWA developed a methodology of four elements for effective apparent losses management process (AWWA 2009) as shown in Figure 4.

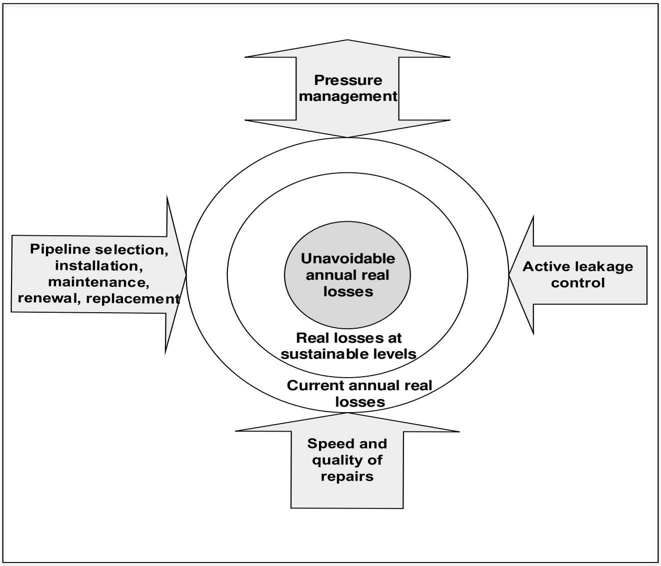



**Figure 3.** The four basic leakage management activities which constrain annual real losses (adapted from (Wu *et al.* 2011)).

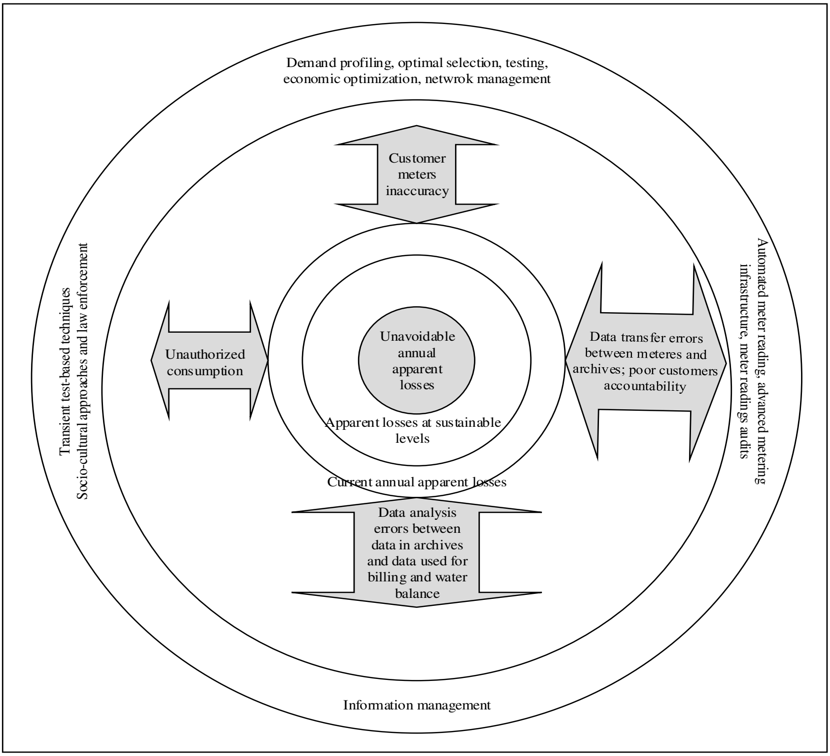



**Figure 4.** A set of four potential approaches to manage apparent losses in WDNs (Adapted from (AWWA 2009)).

Although there is growing interests in research and application of water loss management strategies worldwide, the progress in developing countries in this context is found to be delayed. The specific conditions of WDNs in developing countries such as the intermittent operation, the high rates of water losses in general and the high levels of apparent losses in comparison to generated figures in developed countries (i.e. 50-65% of NRW in Asian cities is due to apparent losses) (McIntosh 2003), insufficient resources, incapable governance and scanty reliable data (Sharma & Vairavamoorthy 2009) limit the direct application of developed water loss reduction and management tools in developing countries as they are not able to perfectly handle the unique conditions and characteristics of WDNs in developing countries. In some cases, the associated high costs with some tools (i.e. direct real time assessment tools of water losses) limit the practical application of these tools for WDNs in developing countries (Sharma & Vairavamoorthy 2009). Furthermore, the development of decision support guidelines or tools by which it is possible to select the adequate strategies for specific local conditions in the context of water losses management in WDNs is still not available sufficiently at practical levels in developing countries and demands further research (Mutikanga *et al.* 2013).

In the act of continuing the existence of different deficiencies with reference to operation of WDNs in developing countries and the high rates of water losses, there is a need to improve the activities related to management of water losses in these countries. Any improvements in this context will grant mitigation of water scarcity and shortage impacts by balancing the witnessed gaps between available supplies and growing demands through the investment in recovered water. In concurrence with considering different water losses management strategies as principals towards more sustainable water resources management, these strategies are seen as challenges (van den Berg 2015). Within reach, a vast number of strategies with potential in reducing water losses in WDNs is available (i.e. the utilization of advanced techniques like online monitoring, multi-parameter sensors, pressure and asset management, etc.). They are distinguished among each other by their: level of complexity; reliability; productivity and impacts, costs of implementation and operation; and their performance. Accordingly, it is a compound practice that is associated with the nomination of the most convenient strategy and involves several issues as shown in Figure 5.

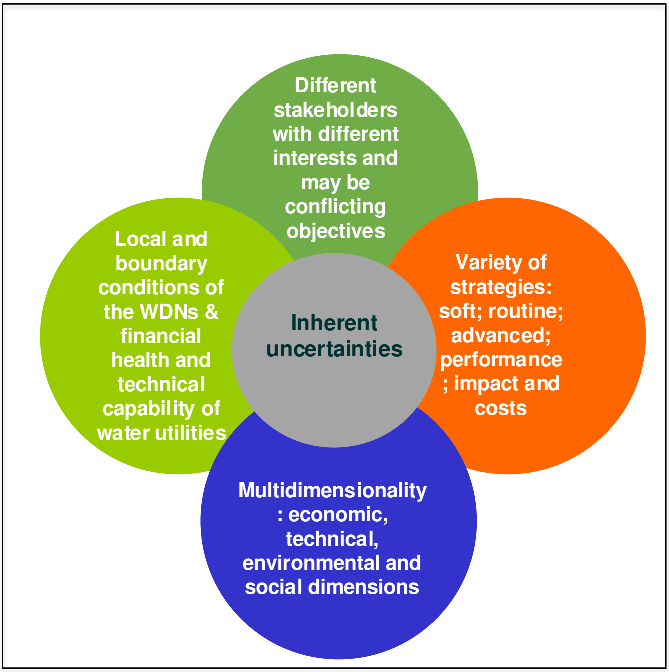



**Figure 5.** Involved issues in the practice of selecting the most appropriate water losses management strategy.

Since the engagement of different stakeholders is seen as a vital tool which can support the implementation of strategic decision making in environmental and/or natural resources management systems (Kotir *et al.* 2017) (i.e. water losses management as a sub issue in the field of water resources management), those decision makers (DMs) are usually having different interests and may be discordant intents towards strategic planning in the context of water losses management. The boundary and local conditions which encompass the characteristics of WDNs (i.e. operational and physical conditions), and water utilities' financial health and technical capabilities which are indicators of water utilities' potency to adopt whether costly and sophisticated strategies or less sophisticated ones are additionally vital in this regard. Moreover, the complexity of this practice is increasing by integrating the multiple sustainability dimensions (i.e. economic, technical, environmental and socio-economic extents). This integration is inevitable to generate more sustainable strategies that are characterized by reliability, adequacy and affordability and to shift towards the trend of the comprehensive sustainability (Shmelev & Van Den Bergh 2016) in the context of water losses management. In addition to previously mentioned issues, the financial shortfalls and inadequate budget allocations among other deficiencies compel water utilities in developing countries to investigate inexpensive techniques with an aim of assessing the rates of water losses in their WDNs. This is required as a diagnostic technique to understand their water systems conditions, and to apply evidently successful water loss reduction strategies within a gradual control and improvement plan. This plan should be carried out phase by phase in line with technical and financial capability of water utilities, and should be arrived based on well-structured decisions.

Essentially, water losses management practice is a course of decision making that aims at handling and addressing all related matters and reducing a set of primary potential strategies to the superlative ones. This in turn calls for the utilization of multi criteria decision making (MCDM) as helpful techniques in this regard.

## 1.4 Multi criteria decision making (MCDM) techniques

Decision Making (DM) can be categorized into two parts: Multi-Objective Decision Making (MODM) and Multi-Criteria Decision Making (MCDM) (Hwang & Yoon 1981). In MODM, the decision space is continuous (i.e. mathematical programming problems with multiple objective functions). While, in MCDM, the decision problem has a set of predetermined decision alternatives and the data is discrete. The MCDM is a full-grown branch within operation research and management science (Behzadian *et al.* 2012; Govindan & Jepsen 2016). It is pertinent to address complicated decision problems that are showing, in mostly, incompatible targets, distinct data forms, multiple concerns and interests of different stakeholders and high inherent uncertainties (Wang *et al.* 2009). The MCDM, in practice, is related to the process of evaluating a set of potential courses of action or strategies. The selection of the most preferred option, sorting options into ordered classes and/or ranking of options from the superior one to unfavorable one are all forms of evaluation within MCDM (Durbach & Stewart 2012).

The MCDM techniques have a great potential in evaluating real-world cases with multiple quantitative and/or qualitative criteria. Their work environment is characterized by certain; uncertain; risky decision making with an aim of finding out the most appropriate course of strategy; policy; choice or action amongst various at hand alternatives (Kumar 2010). The frequent practice in the employment of MCDM shows their cruciality in the allocation of the limited resources between competing options or strategies (Diaby *et al.* 2013). Their usefulness is recognized in cases where the integration of hard data with subjective evaluations and preferences is required to accomplish trade-off amidst desirable issues and to incorporate numerous DMs (Dolan 2010). Mathematics, economics, information systems, computer technologies, behavioral decision theory and software engineering could be among the major sources of knowledge employed in MCDM (Behzadian *et al.* 2012). Roy (2016) pointed out that this field of science has a massive theoretical and applied research output since the 60s and will maintain its progress in an active conduct.

A broad number of techniques have been evolved to resolve MCDM issues, and their growth is largely motivated by diversification of real-life problems that required the considering of various inconsistent objectives and criteria in addition to DMs' willingness of offering consolidated decision-making techniques which are employing the contemporary promotions in mathematical optimization, scientific computing and computer technologies (Wiecek *et al.* 2008). Moreover, the needs to develop methodological approaches and theories which have potential to treat the complicated problems encountered in engineering, science, management business, and other human activities fields are guiding the growth in MCDM (Behzadian *et al.* 2010). In its core work, MCDM defines first the major objectives, nominates the required criteria, assigns options or alternatives, transforms criteria scales into commensurable units, identifies weights of criteria that indicate the criteria importance, employs mathematical algorithms with an aim of ranking options/alternatives, and finally elects the most convenient ones (Ananda & Herath 2009). In their common view, MCDM techniques are seeking through a procedure of breaking down the overall evaluation of options/alternatives into a group of evaluations with reference to a set of mostly incompatible criteria which are in relevance to the decision problem to improve the decisions making.

The assessment of performance of options/alternatives on each criterion and the procedure of reaching an overall assessment by aggregating assessments across criteria represent the major distinction between different MCDM techniques (Durbach & Stewart 2012). In MCDM methods, the matrix of performance acts as the base of any analysis that is utilizing multiple decision criteria. The performance matrix is composed of columns and rows; the columns represent the evaluation criteria which have to be employed to assess the performance of options/alternatives, while the rows represent options/alternatives which have to be rated, ranked or classified (Diaby *et al.* 2013). There are various protocols employed by different MCDM techniques to draw out the inputs, various structures to demonstrate them, different algorithms to merge them, and diverse approaches to use and illustrate formal outputs in the context of decisions making (Huang *et al.* 2011).

The MCDM techniques are confident and assured techniques (Rahman *et al.* 2015). They have shown to be efficient in participatory approaches within decisions making and in situations where, typically, there is no unrivalled solution is feasible and it is claimed to discriminate amongst a set of potential solutions. The MCDM techniques have been successfully applied in resolving decision-making problems in many fields such as: environmental risk analysis (Linkov & Seager 2011; Mansour *et al.* 2016), flood risk management (Azarnivand & Malekian 2016), environmental sciences and environmental impact assessment (Huang *et al.* 2011; Ruiz-Padillo *et al.* 2016), remote sensing (Potić *et al.* 2016), solid waste management (Maimoun *et al.* 2016), transportation (Karlson *et al.* 2016), energy (Wang *et al.* 2009; Tock & Maréchal 2015), climate change (Kim & Chung 2013), health care (Mühlbacher & Kaczynski 2016; Thokala *et al.* 2016), health technology assessment (Schmitz *et al.* 2016), nanotechnology research (Linkov *et al.* 2011), business intelligence (Pape 2016), information and communication technologies (Cid-López *et al.* 2016), and international politics and laws (Linkov *et al.* 2014).

It is possible to categorize the MCDM techniques into the following three groups: value-based methods, distance-based methods and outranking methods (Goulart Coelho *et al.* 2016). The first group includes multi-attribute utility theory (MAUT), multi-attribute value theory (MAVT)(Keeney & Raiffa 1993), and the analytical hierarchical process (AHP) (Saaty 1990). The major distinction between MAUT and MAVT is that the MAUT is considering, explicitly, the uncertainty utility functions instead of using value functions. While in case of MAVT, value functions are used to demonstrate the level of satisfaction of an option/alternative with respect to one criterion.

Consequently, the comprehensive performance of an option/alternative is resolved by the aggregation of value functions in an index for each criterion (Goulart Coelho *et al.* 2016). The assumptions in AHP method are based on evaluation of options/alternatives by employing pairwise comparisons among the elements of the decision problem in a multilevel hierarchical structure. The evaluation of inconsistency index in AHP method is one of the primary advantages of this method. This evaluation provides an assessment about the level of discrepancies in preferences or judgments during the process of pairwise comparison (Pohekar & Ramachandran 2004).

In the second group of distance-based techniques, the performance of option/alternative is evaluated based on the distance from an alternative with best or worst solution. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method, which has been developed by Hwang and Yoon (1981), is one of the most frequently used techniques. An option/alternative has the outstanding performance when its Euclidean distance is nearest to the ideal solution and farthest to the worst solution (Huang *et al.* 2011).

In the third group of outranking methods which also acknowledged as preference aggregation-based techniques, the evaluation is based on comparing the performance of options/alternatives in pairs to find out if an option/alternative is somewhat as good as another (Cinelli *et al.* 2014). The most two common methods within this group are: Preference Ranking Organization and Method for Enrichment Evaluation (PROMETHEE) (Brans & Vincke 1985), and Elimination and Choice Expressing Reality (ELECTRE) (Roy 1991). The primary steps of PROMETHEE method involves: the defining of preference functions for each criterion; establishment of preference index and preference flows and the ranking of options/alternatives (Ananda & Herath 2009). Since its inception, several versions of PROMETHHE method were developed to resolve more complicated decision problems (Brans & Mareschal 2005). The PROMETHEE family includes PROMETHEE I for partial ranking and PROMETHEE II for the complete ranking of alternatives, PROMETHEE III was proposed for ranking of the alternatives based on intervals, PROMETHEE IV for partial or complete ranking in case there is a continuous set of viable solutions, PROMETHEE V was proposed for multi-criteria optimization under constraints (Brans & Mareschal 1992; Brans & Mareschal 1994) and PROMETHEE VI introduced the notion of the human brain representation (Brans & Mareschal 1995).

The family of ELECTRE methods, uses the pairwise comparison to evaluate the concordance and discordance indices. It verifies if the performance of an option/alternative over one criterion is worse than an acceptable limit (Doumpos & Zopounidis 2014). Several other ELECTRE methods were developed to deal with different real world decision making problems such as: ELECTRE I, II, III, IV, and V.

The most commonly used MCDM techniques are: the Analytical Hierarchical Process (AHP), Multi Attribute Utility Theory (MAUT), Simple Multi Attribute Rating Technique (SMART), Fuzzy Set Theory, Data Envelopment Analysis (DEA), Case-Based Reasoning (CBR), Simple Additive Weighting (SAW), Elimination et Choice Translating Reality (ELECTRE), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Preference Ranking and Organization Method for Enrichment Evaluation (PROMETHEE), and Goal Programming (GP) (Velasquez & Hester 2013; Wang *et al.* 2016). A comprehensive review about the developments of AHP and TOPSIS methods based on employing bibliometric techniques can be found in appended paper of Zyoud and Fuchs-Hanusch (2017b).

In water resources management field, a study conducted by Hajkowicz and Collins (2007) to identify trends of using MCDM techniques in this filed indicated that Fuzzy set analysis, compromise programming (CP), AHP, ELECTRE, and PROMETHEE were respectively the most common used ones. Since the management of water resources systems requires mostly synergistic communications and discussions amongst all DMs and stakeholders who are having various preference goals, decision analysis and MCDM are recognized as a disciplined approach in this context (Abrishamchi *et al.* 2005). Furthermore, the capability of these techniques in handling the issue of conflicts resolutions in water resources management context which usually engages the affected stakeholders in the process of solving the issues surrounding the dominance of one strategy over another, the environmental issues, the technical aspects and the social dimensions makes them useful tools in analyzing these decision problems that broaden to a level of harmonizing and accommodating stakeholder objectives. Figure 6 below displays the general steps in MCDM process.

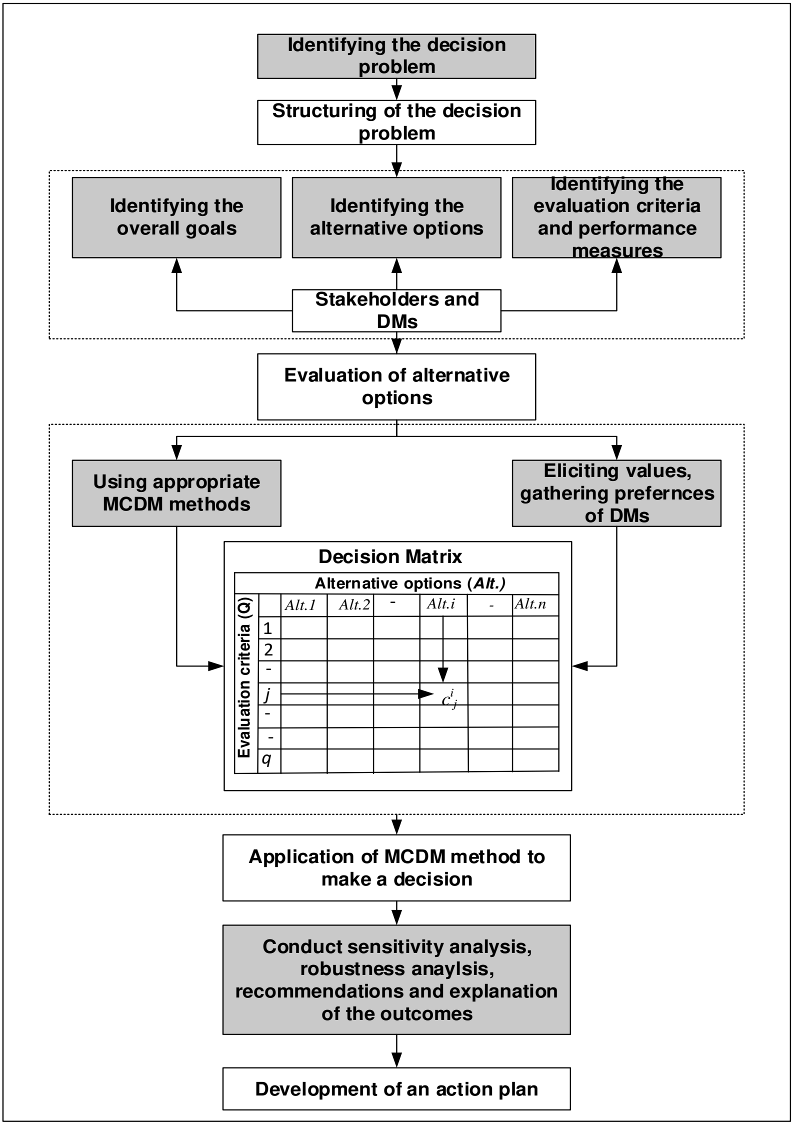



**Figure 6.** General steps in an MCDM process.

## 1.5 Research motivation

During the last periods, the issue of managing water resources more efficiently has become urgent. This was due to several related emerging factors, such as the rapid increase in customers' numbers as a result of rapid population growth and urbanization or the growing awareness of the need to more water resources conservation in combination with climate change effects. Especially, climate change effects may rise the variability of water supplies and the rate of frequency of water-related catastrophes as well as increasing the gap between available supplies and required demands. Accordingly with the aim of facing these challenges, the water sector is required to improve the followed approaches in using the available water resources.

The previous issue becomes more critical for water utilities which are facing deficiencies in the operation of WDNs in the context of water losses. In developed world countries, which have much better technical and financial capabilities to manage and control their WDNs, the status is better in comparison with the developing world countries. The inadequacy of their water supply systems to meet the water needs of increasing number of people, deteriorating and aging systems, intermittent water supply services, insufficient resources, deficiencies in governance, scanty reliable data required in the assessment of performance of WDNs are key challenging issues in addition to the major issue of high rates of water losses. It is estimated that about 55% of the total volume of NRW at global level occurs in developing world countries (Kingdom *et al.* 2006). Moreover, while it is widely reported that a substantial work in developed countries has been devoted in reducing the rates of NRW in their WDNs with an aim of improving the performance of WDNs, an insufficient work has been done in the same context in the developing world (Mutikanga *et al.* 2009).

Another motivation added to previous ones is related to the issue of rising the concerns of different stakeholders over the risks associated with water scarcity and other related issues. As the issue of engagement of a wide collection of stakeholders and DMs in water resources management issues is being emphasized among the developed world, it is still in its infancy stage in most of the developing world and the related techniques are typically less applied. The integration of stakeholders in the decision process is a useful approach in terms of considering the different priority objectives of different stakeholders, realizing a better understanding and assessments of components of water losses management process. Discussions and interactions allow to achieve consensus and concrete actions towards critical issues in water losses management which in turn will strengthen the decision making outcomes, encourage group decision making and lead to compromise solutions. Therefore, it was a major motivation to promote the introducing and the application of decision making techniques in the context of water resources management (i.e. water losses management) in developing countries as it will lead to a better control of water losses in their water systems.

Furthermore, the critical risks appeared in association with adopting intermittent water supply services (i.e. risks mentioned in details in **Section 1.2**), motivate the work to explore efficient approaches with high potential in mitigating these risks. This in turn will improve the water supply services in developing countries and the performance of their water systems.

## 1.6 Research gaps

Most of developed models and techniques that are addressing issues related to intermittent water supply services in developing countries are focused mainly on two approaches. The first one is concerned with the development of methodologies to promote the switching from intermittent supply to continuous supply. While, the second approach is concerned with the development of appropriate design and optimization tools to analyze and realize the hydraulics of these systems. The analyzing of inequality and recognizing the associated health and quality risks have attracted much attention by researches in this filed. McIntosh (2003) suggested that the issues of governance and tariff are the core of the intermittent water supply problem. Accordingly, the author proposed the gradual introduction of continuous supply (zone by zone). In parallel with that, the author suggested the imposing of higher tariffs on zones of continuous service to benefit from the extra funds in extending the service (McIntosh 2003). The same approach as in the previous one was proposed by Myers (2003). Seetharam and Bridges (2005) proposed the development of a hybrid management contract model by which the government will hold the assets and funds, and the private sector will be responsible over changes and increasing the efficiency with an aim to switch from intermittent to continuous water supply service. Klingel and Deuerlein (2008) and Klingel and Nestmann (2014) suggested that the introduction of continuous mode of water supply is the warrantor for convenient functioning water systems and it can be achieved through a thorough knowledge of technical causes of intermittent supply.

There is much research that has focused on the development of proper techniques to optimize the intermittent water supply services motivated by the fact that the intermittent supplies in developing countries are inevitable practices (at least in the foreseeable future). Trifunović and Abu-Madi (1999) developed a model to examine the hydraulic behavior of intermittent water supply systems. Vairavamoorthy *et al.* (2001), Vairavamoorthy and Elango (2002), Totsuka *et al.* (2004) and Vairavamoorthy *et al.* (2008) focused on the development of tools of design of sustainable water distribution systems in developing countries which proved to be successful in achieving least cost design and equitable distribution in intermittent water supply systems. De Marchis *et al.* (2010) and De Marchis *et al.* (2011) studied the dynamic process of network filling in intermittent water supply systems to analyze the inequality in supplying customers. Fontanazza *et al.* (2007) and Fontanazza *et al.* (2008) developed a numerical model and performance indices to evaluate the equity, and to recognize the advantaged and disadvantaged users in intermittent water supply systems. Nyende-Byakika *et al.* (2012) and Nyende-Byakika *et al.* (2012) modeled flow regime transition in intermittent water supply networks using the interface tracking method to help in managing them much better.

Other researchers have tackled the issue of water contamination and health risks associated with intermittent supply. Kumpel and Nelson (2013) compared the microbial water quality in intermittent and continuous water supply systems and found from testing different collected samples that indicator bacteria were at higher concentrations and more frequently in the intermittent system, E coli was rare in continuous (0.7%) while in intermittent (31.7%) and Total Coliform was at high concentrations in both systems after rainfall events. Kumpel and Nelson (2014) studied the mechanisms that affect the water quality in intermittent water supply systems by continuous measuring of pressure and physicochemical parameters and collecting samples to test them for E. coli and Total Coliform throughout supply cycles. They found that all conditions lead to contaminant intrusion (pathway, source, low pressure) were common in the tested intermittent water supply system. Fontanazza *et al.* (2015) evaluated potable water contamination through leaks during intermittent supply and pressure transient based on experimental setup. Vairavamoorthy *et al.* (2007) developed a software tool with potential to predict the risks associated with contaminant intrusion into intermittent water distribution systems and the results were several thematic maps which identified sections of the system that were most at risk.

Although some of previous studies reported the issue of water losses in intermittent water supply systems, this was in the form of recommendations and not as an essential part. Therefore, a knowledge gap is still existing with respect to the role of controlling water losses, principally in developing countries, in eliminating the underlying causes of intermittent supply. In addition to benefits of conserving water as rare natural resource and promoting the financial status of water utilities in association with water loss reduction, the reduction of water losses will be a first step for gradual transition from intermittent to continuous supply services. This is applicable by the investment in the recovered water which has high opportunity costs in alleviating the water shortage.

In the context of applying MCDM techniques to solve water loss problems in developing countries, there are several studies that have attempted to investigate this issue. ELECTRE III method has been used to structuring a multi-criteria model that aims to assist in water loss management activities in Brazil based on group decision making (Morais *et al.* 2014). As a long-term planning method for management of water losses in Kampala city located in Uganda, PROMETHE II has been used as a strategic tool (Mutikanga *et al.* 2011). PROMETHEE V method has been employed to support DMs in nominating a group of feasible options to rehabilitate water supply networks with detected leaks (Fontana & Morais 2013). Finally, ELECTRE II and ELECTRI TRI have been used to structuring a decision model that aims to support DMs in maintenance management activities and reducing of water losses in WSNs (Trojan & Morais 2015). Although the previous developed models are well structured and produced sound outputs, some of them reported difficulties in understanding some of their evaluation tools which were questionable and perceived by DMs as a black box (Mutikanga *et al.* 2011).

Accordingly, the nomination of MCDM techniques that have sufficient potential in stating and structuring the decision problem of water losses management in intermittent water supplied systems in a clear and understandable course will be an essential issue in this research. Moreover, and due to lack of sufficient financial resources and allocating budgets, water utilities in developing countries seek for inexpensive tools to manage water losses in their systems. Most of the already developed techniques in the field of water losses management do not completely address the exclusive features of WDNs in the developing world. There is still a need for specific arrangements to adopt the existing methods while considering the unique boundary conditions and characteristics of WDNs in developing countries. Therefore, the development of appropriate frameworks to manage water losses in intermittent supplied systems by introducing MCDM techniques is the main target of this research.

## 1.7 Research objectives

Based on the research motivation and needs stated in **Section 1.6**, the major objective of this research is to develop appropriate techniques and methodologies with an aim of aiding water utilities, particularly in developing countries, to make better decisions on how to improve their control over water losses in their WDNs and to boost the efficiency of their water supply systems. Furthermore, it aims to develop a decision support framework for planners, DMs and stakeholders with potential of interaction capabilities and of providing detailed insights into the problem of water losses. This in turn will help in evaluating alternatives that are required to determine the optimum strategies to manage water losses in WDNs and to assess water losses considering: the unique characteristics and boundary conditions of WDNs, the competing objectives and stakeholders and DMs preferences on objectives. The specific objectives of this research include:

1. Introducing the principles and applications of MCDM techniques in the process of management of water losses in intermittent water supply systems in developing countries to:

1.1 Improve the planning policies of water utilities.
1.2 Leading to better control over water losses based on consented and transparent decisions.
1.3 Increase the efficiency of water utilities in developing countries.
1.4 Promote the gradual switching from intermittent to continuous supply services by investing in the recovered water to improve the services.

2. Development of an efficient decision support framework to manage water losses by:

2.1 Development of a MCDM framework with the purpose of selecting the most appropriate solutions to reduce water losses in intermittent water supply systems.
2.2 Development of a framework to identify the zones within a water supply network that have higher priority in terms of water losses with an aim of applying the selected best strategy from the above model over zones with high criticality of water losses (through gradual improvement and long term planning).
3. Demonstrating the proof-of-concept of the different developed frameworks by applying them to a real–world case studies.

To fulfill the above specified objectives, this research examines the following research questions:

- What is the best approach to demonstrate the investigated decision problem in an attractive and understandable mode?
- What are the most convenient MCDM techniques with potential in a) controlling and structuring the decision problem and b) providing simple and clear evaluation tools to be used by DMs and stakeholders?
- What are the most important factors that should be considered in identifying the decision problem elements?
- Is there a need to employ more or less sophisticated MCDM techniques to the decision problem?
- If there could be clear differences in the outputs of complex MCDM techniques in comparison to less sophisticated techniques when they are applied to the same decision problem in the context of water losses management?
- How can uncertainty issues be appropriately modelled in the decision making problem?
- How should the developed frameworks be applied for decision making in water loss management in water supply systems of developing countries?

# 2 Research methodology[2]

The primary tasks involved in accomplishing the objectives defined in **Section 1.7** are presented in Figure 7 which displays the methodological framework followed in this research. As explained previously, the major purpose of this framework is to assist water utilities in developing countries to manage and control water losses in their water supply systems more efficiently as a part of long-term decision making and planning which consecutively will improve water utilities services and provide opportunity of gradual shift towards continuous supply services. To fulfill the major targets of: i) promoting the introduction of MCDM techniques, which are less applied, in the planning policies of water utilities in developing countries and particularly in the context of water losses management, ii) integrating the sustainability dimensions into the proposed water losses management framework which will in turn provide sustainable strategies, iii) considering the commonly conflicting objectives of different stakeholders, and iv) the development of appropriate tools to asses water losses with an aim of helping in gradual application of high potential strategies of reducing water losses over zones with high criticality in terms of water losses and associated risks. The following key tasks are therefore being carried out:

**Task 1**- For the development of a water loss management framework, the decision problem was identified throughout a hierarchical structure module. This framework was developed based on a critical review of the available literature on water loss management approaches, consultations with experts in the field and by considering local conditions of the scrutinized case study.

**Task 2**- Selection of an appropriate MCDM technique for the decision module. This task was initiated by employing one of extensively used MCDM techniques, precisely AHP method. This task was motivated by the need to introduce to stakeholders and DMs simple techniques with high potential in structuring and analyzing complex decision problems. Furthermore, its simplicity in terms of use, understandability and the required effort to reach a conclusion was crucial in the selection process.

**Task 3-** To manage inherent uncertainties in the decision making process, fuzzy set theory has been incorporated with AHP later on. This is followed by a comparative analysis between the two approaches (i.e. the traditional AHP approach and Fuzzy AHP approach). It is seeking to address the differences that might arise from employing different MCDM techniques towards a single decision problem.

**Task 4-** Further to the previous work, an integrated methodology of Fuzzy AHP and Fuzzy TOPSIS is proposed in the same context as mentioned above. This was also motivated by the potential of this integrated approach to handle the decision problem in an efficient manner. Moreover, this method allows for reducing the computational complexity, and the agility in the decision process, and enables the incorporation of uncertainties in the decision making process.

**Task 5-** The outcomes of Task 2, Task 3 and Task 4 in terms of prioritizing and ranking the potential strategies of managing water losses are analyzed and compared. This aims to evaluate the robustness of the developed framework for strategic water loss management decisions as it is tested by several MCDM techniques.

**Task 6-** A hybrid framework of Fuzzy AHP, fuzzy synthetic evaluation (FSE) and ordered weighted averaging operator (OWA) for evaluation of a water loss risk index (WLRI) is proposed and applied to a case study. The intent is to assist water utilities in arriving at a structured decisions to diagnose

[2] Parts of this chapter have been published in (Zyoud *et al.* 2016a; Zyoud *et al.* 2016b; Zyoud & Fuchs-Hanusch 2017a; Zyoud & Fuchs-Hanusch 2017b).

the criticality of zones within WSNs according to the associated WLRI. Accordingly it helps in applying the most appropriate strategy with evident success in reducing water losses over zones with higher criticality in terms of water losses and associated risks. This framework involves the most important factors that affect water losses in WSNs and the possible consequences in terms of social and environmental impacts. The approach is extended by incorporating Monte Carlo simulation analysis. This enables to incorporate a probabilistic approach which eliminates the limitations of deterministic and fuzzy group decision making methods.

**Task 7-** In association with identifying the previous tasks, a group of experts who act as the most influential actors in the water sector in Palestine is identified, involved in the consultations about the decision problem structure and its components and engaged as participants in the evaluation process. This was in parallel with identifying the case study, Nablus Water Distribution System (NWDS)-Nablus City-Palestine, with an aim to proof the developed concepts and methodologies. The case study represents to a large extent water distribution systems in developing countries and faces as well water loss-related as water scarcity and intermittent supply service problems. The data and evaluations required in processing the developed methodologies have been collected from different sources.

**Task 8-** The robustness and reliability of outcomes of the developed methodologies have been evaluated and tested by performing sensitivity analyses, scenario analysis and different statistical significance tests.

**Task 9-** An additional work to create an informative analysis about research activities related to AHP and TOPSIS methods and to document the growing interest in these methods is carried out. These two methods are highly active fields of research among MCDM methods and they are a good representative example of the diverse applications of MCDM methods in conjunction with other disciplines. Bibliometric techniques which are frequently used to evaluate and measure the performance of science and technology at national or international levels within a given discipline or body of literature are used in this analysis.

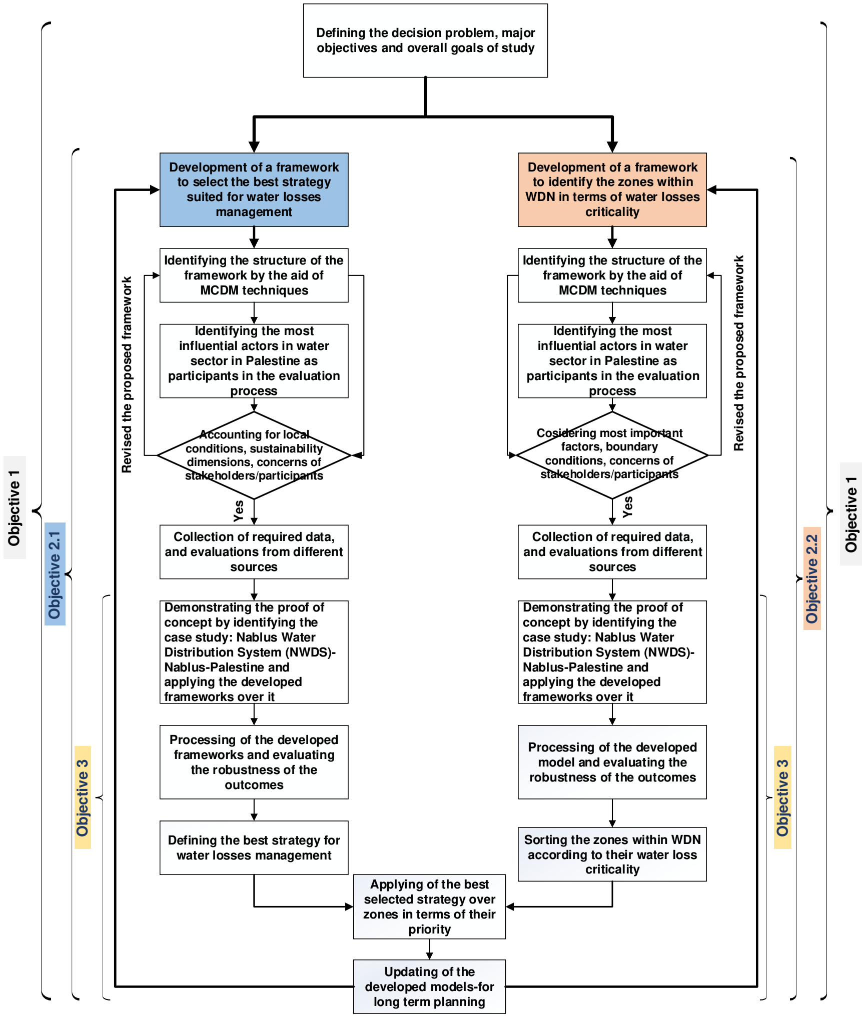



**Figure 7.** Proposed methodology and major tasks within the proposed frameworks.

## 2.1 Development of a framework for strategic water loss management decisions

### 2.1.1 Structuring of the decision problem

It is proposed to identify the decision problem by the aid of a hierarchical structure module. This is motivated by the fact that, a major job to resolve complex decision problem is structuring the problem into sub problems. Primarily, the hierarchical structure is similar to the shape of a tree (i.e. the root represents the overall goal of the decision problem and the branching elements from the goal act as the main criteria) (Del Vasto-Terrientes *et al.* 2015). The main criteria are splitting into other blocs of evaluation criteria. These evaluation criteria are available in the intermediate levels of the structure. The number of levels of main and evaluation criteria is determined by the complexity of the decision problem (i.e. more complex problem has more levels of main and evaluation criteria). The set of options/alternatives/strategies has to be found in the lowest level of the structure. This type of structuring the decision problem enables DMs to assess and analyze alternatives with reference to individual subgroups of criteria and/or evaluation criteria (Del Vasto-Terrientes *et al.* 2015). The development of reliable structure entails an inclusive literature review about the state of the art, scrutinizing closely and thoroughly the experts' opinions in the field, taking into consideration the boundary conditions of the examined case study and thinking over all decision problem's dimensions.

Reaching perfect decisions implies a clear definition of the overall goal. In the examined case it was devoted to recognize the best alternative among a group of key alternatives to efficiently manage water losses. The sustainability aspects should be guaranteed and commonly guide the balance between economic, technical, environmental and socioeconomic dimensions. The economic aspects include the financial viability of alternatives such as initial costs, operational and maintenance costs and opportunity costs which should provide the maximum economic benefits. The environmental aspects measure the environmental impacts of the alternatives during their operation. The environmentally sustainable alternative is the one that minimizes the use of natural resources and the amount of wastes in addition to the required energy input. The technical aspects measure the capacity of alternatives to execute their functions in effective, ease of use and flexible features. Lastly, the socio-economic aspects measure the willingness of the community to adopt the alternatives. They can be perceived in terms of the alternatives' impacts on health of community and economic benefits such as low costs to the users and low impacts on the existing community livelihoods.

Furthermore, fulfilling the water utilities' mission of improving water supply services, promoting the public health of customers, preserving water and maintaining affordable services should be a prerequisite to a successful development and application of the proposed framework. Identifying of appropriate alternatives with potentials to reach the main objectives is following the definition of the overall goals. For effective decision making, the better designation of alternatives is decisive. The assessment of these alternatives should be done in terms of their comprehensive advantages and the associated costs, impacts and benefits of implementation. Differentiating among alternatives and assessing their performance in meeting the overall goals were realized by establishing a group of evaluation criteria, which are in relevance to the sustainability aspects. The evaluation criteria are nominated by benefiting from literature and recent research on management of water losses (Alegre *et al.* 2006; Fanner *et al.* 2007; Morais & de Almeida 2007; AWWA 2009; Delgado-Galván *et al.* 2010; Mutikanga *et al.* 2011, 2013; Morais *et al.* 2014; Trojan & Morais 2015), discussions with experts and local professionals in the field and accounting for the boundary conditions of the scrutinized case study. The set of evaluation criteria are grouped according to their relevancy to the sustainability aspects and discussed in details as follows:

-Generation of revenue (Economic category; preference trend: maximize): the potential of the alternative to produce and increase the revenue.
-Costs of implementation (Economic category; preference trend: minimize): the associated costs with the alternatives' implementation.
-Operation and maintenance costs (Economic category; preference trend: minimize): the associated costs with controlling and up keeping the alternative.
-Period of benefit (Economic category; preference trend: maximize): the useful life span of the alternative which is most preferable in case the alternative has longer life cycle.
-Water preservation and reduction of waste (Environmental category; preference trend: maximize): the ability of the alternative to maximize water savings and to minimize the pressure on the natural resources.
-Saving of energy (Environmental category; preference trend: maximize): the potential of the alternative to reduce the required energy and greenhouse emissions.
-Reliability of supply (Technical category; preference trend: maximize): the capability of the alternative to save most continuous supply service and to reduce the occurrence of supply interruptions. It is most preferable in case the alternative has lower level of leaks frequencies.
-Flexibility potential (Technical category; preference trend: maximize): the capability of the alternative of being adjusted to meet variation in needs and uncertainties.
-Affordability (Socio-economic category; preference trend: maximize): the impact of the alternative on water tariff. It is most preferable in case the alternative has stable effect on tariff.
-Water quality (Socio-economic category; preference trend: maximize): the potential of the alternative in improving water quality.

Figure 8 illustrates the developed hierarchical structure of the framework of water losses management. More details about the elements of the structure can be found in Zyoud *et al.* (2016b). The overall goal of building a strategy for water losses management holds the upper position in the hierarchical structure. It is followed by the set of main criteria as sustainability dimensions. They are splitting up into their relevant evaluation criteria in the third level. The evaluation criteria have been employed to assess alternatives' performance and to distinguish among alternatives in terms of meeting the comprehensive objectives. The last level is kept for the alternatives which have been connected to the set of evaluation criteria in the upper level.

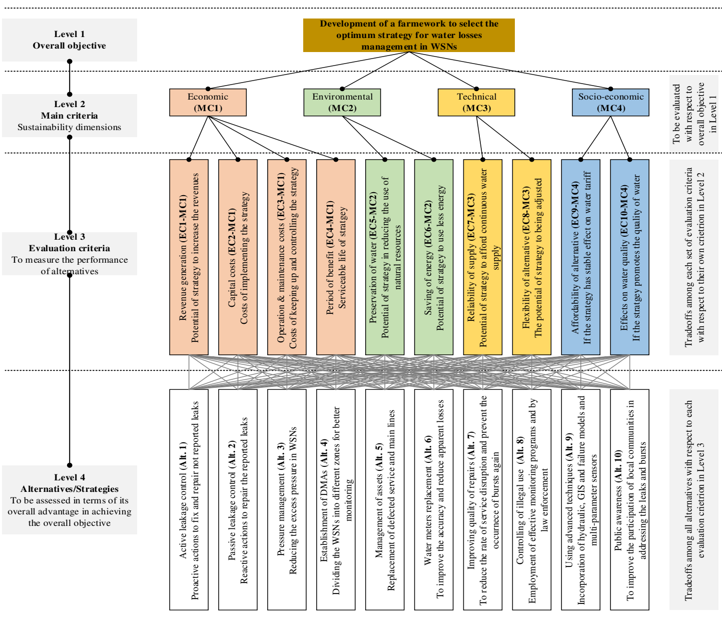



**Figure 8.** Illustration of water loss management hierarchical structure framework.

### 2.1.2 Employing of the Analytic Hierarchy Process (AHP)

AHP is one of the widely used pairwise comparison techniques amongst the MCDM methods (Hajkowicz & Collins 2007). The selection of this method was due to clearness of its mathematical characteristics, the ease of securing the required input data, and the efficiency in handling qualitative and quantitative data, as well as structuring the complex decision problems based on a hierarchical structure module **(Section 2.1.1)**. The main three governing principles in AHP are:

1- Decomposition of the problem into a hierarchical structure, which provides DMs with a better focus on specific criteria and sub-criteria when allocating the preferences.
2- Comparative judgments by executing pairwise comparisons through decision tables or matrices to derive the priorities of the elements of the decision problem in each level, and
3- Aggregation of the priorities (Veisi *et al.* 2016).

The generated decision matrix is a square matrix, as shown below in Eq. 1, using positive entries according to the numerical scale in Table 1. Each entry represents the preference of a DM for one element over another.

$$A_{n*n} = (a_{ij}) = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ & 1 & \cdots & a_{2n} \\ \vdots & 1/aij & \ddots & \vdots \\ & & \cdots & 1 \end{bmatrix} \quad (1)$$

A is the decision matrix, $a_{ij}$ are pairwise comparisons between elements *i* and *j* for all $i,j \in \{1, 2, \ldots\ldots, n\}$

**Table 1.** Saaty numerical scale for pairwise comparisons in AHP

| Judgment term | Saaty ($a_{ij}$) |
|---|---|
| Absolute preference (element *i* over element *j*) | 9 |
| Very strong preference (*i* over *j*) | 7 |
| Strong preference (*i* over *j*) | 5 |
| Weak preference (*i* over *j*) | 3 |
| Indifference as regards *i* and *j* | 1 |
| Weak preference (*j* over *i*) | 1/3 |
| Strong preference (*j* over *i*) | 1/5 |
| Very strong preference (*j* over *i*) | 1/7 |
| Absolute preference (*j* over *i*) | 1/9 |
| When compromise is needed-intermediate values | 2,4,6,8…..1/2,1/4, 1/6, 1/8 |

The derivation of elements' relative weights is executed by estimating the eigenvalues, and the results will be a priority matrix. The measurement of accuracy of pairwise comparisons is performed by calculating the consistency index (*CI*) and the consistency ratio (*CR*) (Delgado-Galván *et al.* 2010) as shown in equations below:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2)$$

where $\lambda_{max}$ the principal eigenvalue, and *n* the order of the matrix. The *CI* then can be compared to that of a random consistency index (*RI*), which is displayed in Table 2.

**Table 2.** Saaty values of random consistency

| Matrix Size (*n*) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Random CI (*RI*) | 0.00 | 0.00 | 0.52 | 0.89 | 1.11 | 1.25 | 1.35 | 1.40 | 1.45 | 1.49 |

The *CR* for the same order matrix is given by the following equation:

$$CR = \frac{CI}{RI} \quad (3)$$

The consistency ratio (CR) should be maintained less than 10%. In case of CR values larger than 10%, the inconsistency level should be improved by reducing or augmenting the most inconsistent value to the next evaluation point step by step (Calizaya *et al.* 2010). The global weights can be derived by aggregating the priority weights along the track starting from the top of the hierarchical structure to the lowest level and multiplying the priority weights along this track.

To aggregate the preferences of all groups of DMs, two methods are proposed: The first one is the geometric mean method (GMM), in which the geometric mean for the individual preferences of DMs have been used as elements in the matrices of the pairwise comparison, and then they are prioritized and their weights are derived (Contreras *et al.* 2008), while the second is using the weighted arithmetic mean method (WAMM) (Ramanathan & Ganesh 1994), in which the priorities are computed and then combined using the WAMM. The process of aggregation of the individual/group preferences is working in such a trend, that the whole groups become a new individual by combining individual opinions to obtain a single opinion (Ramanathan & Ganesh 1994).

To check the stability and robustness of obtained outcomes that are based on subjective assessments of experts (Govindan *et al.* 2015; Molinos-Senante *et al.* 2015), a sensitivity analysis is carried out. The purpose of the sensitivity analysis is to evaluate how the variations in weights of main criteria will impact the ranking of alternatives in the last level. By employing the capabilities of Expert Choice Software (Expert Choice 2016), it is possible to identify the stability intervals in which the changes in weights of main criteria will not influence the rankings of alternatives (Zyoud *et al.* 2016b). Figure 9 below displays the detailed flowchart of the AHP method that is used to build the water loss management framework and to nominate the most appropriate strategy. More details can be found in Zyoud *et al.* (2016b).

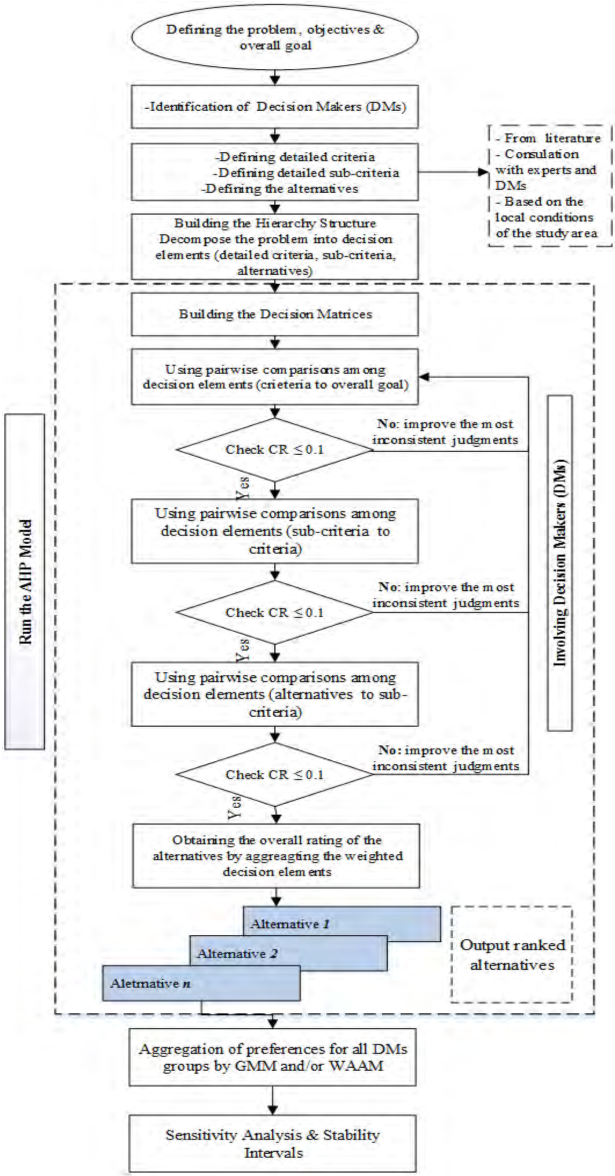



**Figure 9.** Flowchart of AHP method used to build a water loss management framework.

## 2.1.3 Employing of the Fuzzy Analytic Hierarchy Process (Fuzzy AHP)

Regardless the successful application of traditional AHP method, it is always criticized for its incompetence in managing inherent uncertainties which could result from connecting whole numbers to the understanding of DMs. Therefore, it appears to be ineffective to be applied to decision problems that are characterized by their ambiguity (Javanbarg *et al.* 2012). Accordingly, the incorporation of fuzzy set theory with traditional AHP is essential in handling and dealing with the uncertainty issue. This theory is with high potential to map insufficient information, perceptions and approximations to generate well-structured decisions by using membership functions. In this theory, a group of elements are belonging to a space that has no exact defined boundaries, and the objects can be taken on membership values with an interval of [0, 1]. This in turn considers a degree of membership (Zadeh 1965). While, in case of a crisp set, an object could belong to a group of elements or not. Hence, the DMs are able to give interval judgments instead of fixed values (Kabir & Sumi 2014). The fuzzy extension of AHP, Fuzzy AHP, which uses triangle fuzzy numbers (TFNs) organized in fuzzy pairwise comparison matrix, is adequate in dealing with the hierarchical ratings of fuzzy decision problems (Calabrese *et al.* 2013).

The membership function for a triangular fuzzy number $\tilde{A}$ shown in Figure 10 on space $R \rightarrow [0, 1]$ with basis symbolized by ($l$, $m$, $u$) can be specified as follows:

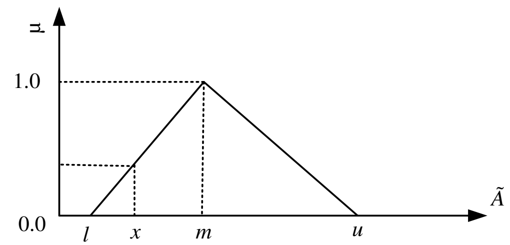



**Figure 10**. Representation of triangular fuzzy number (TFN) with basis denoted as ($l$, $m$, $u$).

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, & x \leq l \\ \frac{x-l}{m-l}, & l \leq x \leq m \\ \frac{x-u}{m-u}, & m \leq x \leq u \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

The ($l$, $m$, $u$) parameters are related to the lowest possible, the most preferable and the highest possible values, respectively. They are describing the fuzzy cases where ($l < m < u$).

In case there are two triangle fuzzy numbers $\tilde{A} = (a_1, a_2, a_3)$ and $\tilde{B} = (b_1, b_2, b_3)$, the associated operational rules will be as follows:

$$\tilde{A} \oplus \tilde{B} = (a_1, a_2, a_3) \oplus (b_1, b_2, b_3) = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \quad (5)$$

$$\tilde{A} \otimes \tilde{B} = (a_1, a_2, a_3) \otimes (b_1, b_2, b_3) = (a_1 b_1, a_2 b_2, a_3 b_3) \quad (6)$$

$$\tilde{A}^{-1} = \left(\frac{1}{a3}, \frac{1}{a2}, \frac{1}{a3}\right) \quad (7)$$

The symbol ⊕ indicates the extended summation of the two triangle fuzzy numbers, while ⊗ indicates the extended multiplication of these two numbers.

#### 2.1.3.1 Derivation of priority weight vectors of different decision elements by Fuzzy AHP

Several methods have been developed with an aim of deriving the priority weights of elements of hierarchical structure in Fuzzy AHP. Among them, the extent analysis Fuzzy AHP which has been proposed by Chang (1996). It is widely employed in this context and the following steps clarify its procedure in deriving the priority weights:

**Step 1:** Performing pairwise comparisons in the form of tradeoffs among the elements in each level of the hierarchical structure with respect to their origin in the upper level using fuzzy numbers. The arrangement of the comparison matrices shown as below:

$$\tilde{A} - \left(\tilde{a}_{ij}\right)_{n*n} \begin{bmatrix} (1,1,1) & (l_{12}, m_{12}, u_{12}) & \cdots & (l_{1n}, m_{1n}, u_{1n}) \\ (l_{21}, m_{21}, u_{21}) & (1,1,1) & .. & (l_{2n}, m_{2n}, u_{2n}) \\ \vdots & .. & \ddots & \vdots \\ (l_{n1}, m_{n1}, u_{n1}) & (l_{n2}, m_{n2}, u_{n2}) & \cdots & (1,1,1) \end{bmatrix} \quad (8)$$

The used values for pairwise comparisons in Fuzzy AHP based on utilizing the scale shown in Table 3

**Table 3.** Proposed fuzzy scale for pairwise comparisons in Fuzzy AHP

| Degree of importance (Fuzzy number) | Linguistic variables | Positive TFN | Reciprocal TFN |
|---|---|---|---|
| $\tilde{1}$ | Equal important | (1, 1, 1) | (1, 1, 1) |
| $\tilde{3}$ | Weak important | (1, 3, 5) | (1/5, 1/3, 1) |
| $\tilde{5}$ | Moderate important | (3, 5, 7) | (1/7, 1/5, 1/3) |
| $\tilde{7}$ | Strong important | (5, 7, 9) | (1/9, 1/7, 1/5) |
| $\tilde{9}$ | Extreme important | (7, 9, 9) | (1/9, 1/9, 1/7) |

**Step 2:** For the aggregation of preferences of *t* DMs and with the aim of building the final pairwise comparison matrix, three different scenarios of aggregation are proposed:

1. Weight aggregation method 1 (WAM1) (Yazdani-Chamzini & Yakhchali 2012)

$$\widetilde{w}_{ij} = (Lw_{ij}, Mw_{ij}, Uw_{ij}) \quad (9)$$

$Lw_{ij}$ = min$_t$ $Lw_{ijt}$, $Mw_{ij} = \frac{1}{T}\sum_{t=1}^{T} Mw_{ijt}$, $Uw_{ij}$ = max$_t$ $Uw_{ijt}$

$\widetilde{w}_{ij}$ = the triangular fuzzy priority weight of *i*th criterion in comparison to *j*th criterion

2. Weight aggregation method 2 (WAM2) based on arithmetic operator (Khazaeni *et al.* 2012)

$Lw_{ij} = \frac{1}{T}\sum_{t=1}^{T} Lw_{ijt}$, $Mw_{ij} = \frac{1}{T}\sum_{t=1}^{T} Mw_{ijt}$, $Uw_{ij} = \frac{1}{T}\sum_{t=1}^{T} Uw_{ijt}$

3. Weight aggregation method 3 (WAM3) which employed the geometric mean of preferences (Jaiswal *et al.* 2015)

$Lw_{ij} = (\prod_{t=1}^{T} Lw_{ijt})^{1/t}$, $Mw_{ij} = (\prod_{t=1}^{T} Mw_{ijt})^{1/t}$, $Uw_{ij} = (\prod_{t=1}^{T} Uw_{ijt})^{1/t}$

**Step 3:** This step is devoting to prioritize the elements of the hierarchical structure (i.e. main criteria, evaluation criteria and alternatives) based on the basis of Chang's extent analysis technique (Chang 1996). If it is supposed that $X = \{x_1, x_2, \ldots, x_n\}$ represents an object set, and $U = \{u_1, u_2, \ldots, u_m\}$ represents the goal set. Accordingly, every object is taken into consideration. Later on, the extent analysis associated with each goal ($gi$) is executed. For each object, the $m$ extent analysis values can be acquired with the following codes: $M_{gi}^{1}, M_{gi}^{2}, \ldots\ldots, M_{gi}^{m}$. All values of the extent analysis are TFNs, ($i = 1, 2, \ldots, n$), and ($j = 1, 2, \ldots, m$). The following equations display the value of fuzzy synthetic extent analysis with respect to the $i$th object:

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes [\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}]^{-1} \quad (10)$$

$$\sum_{j=1}^{m} M_{gi}^{j} = (\sum_{j=1}^{m} l_i, \sum_{j=1}^{m} m_i, \sum_{j=1}^{m} u_i) \quad (11)$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j} = (\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i) \quad (12)$$

$$[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right) \quad (13)$$

For two fuzzy synthetic extent values e.g. $S_2 = (l_2, m_2, u_2) \geq S_1 = (l_1, m_1, u_1)$ shown in Figure 11, it is possible to define the degree of possibility between them as below:

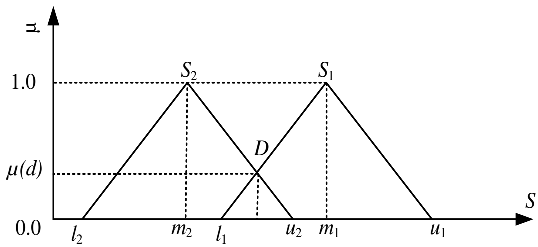



**Figure 11.** Illustration of intersection between two TFN numbers.

$$V(S_2 \geq S_1) = hgt(S_2 \cap S_1) = \mu(d) = \begin{cases} = 1 & \text{if } m_2 \geq m_1 \\ = 0 & \text{if } l_2 \geq u_2 \\ = \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \text{otherwise} \end{cases} \quad (14)$$

In Eq. 14, $d$ represents the ordinate of the highest intersection point between the two TFNs. The comparison between $S_1$ and $S_2$ required the calculation of the two values: $V(S_2 \geq S_1)$ and $V(S_1 \geq S_2)$. For a convex fuzzy number to be greater than $k$ convex fuzzy numbers $S_i$ ($i = 1, 2, \ldots, k$), the degree of possibility can be explained as follows:

$$V(S \geq S_1, S_2, S_3, \ldots\ldots, S_k) = V[(S \geq S_1) \text{ and } (S \geq S_2) \text{ and } \ldots\text{and } (S \geq S_k)] = \min V(S \geq S_i) \quad (15)$$

By assuming $d'(C_i) = \min V(S_i \geq S_k)$ for $k = 1, 2, \ldots, n$ ($i \neq k$), the vector of weight can be awarded by:

$$W' = [d'(C_1), d'(C_2), d'(C_3), \ldots\ldots, d'(C_n)]^T \quad (16)$$

where $C_i$ ($i$= 1, 2, …, $n$) are $n$ elements.

Lastly, the weight vectors should be normalized, and the results will be in the form of non-fuzzy numbers.

$$W = [d(C_1), d(C_2), d(C_3), \ldots\ldots, d(C_n)]^T \quad (17)$$

Despite the wide use of extent analysis Fuzzy AHP method (Kubler *et al.* 2016), it has a failure of generating zero values of priority weights in cases of existence of extreme evaluations (Jakiel & Fabianowski 2015). Moreover, Wang *et al.* (2008) criticized the approach of using the normalized degrees of possibility as an index in deriving the priority weights and emphasized that, they are able only to display to what level a TFN is greater than other TFNs. Calabrese *et al.* (2013) suggested a modified method. The new method based on the modified normalization formula which has been proposed by Wang and Elhag (2006) and Wang *et al.* (2008). Therefore, in addition to using the Fuzzy AHP method, which is relied on the extent analysis method of Chang (1996), the procedure that has been proposed by Kabir and Sumi (2014) and Calabrese *et al.* (2013), and based on the modified normalization method suggested by Wang and Elhag (2006) and Wang *et al.* (2008) is followed. Herein, it is indicated as modified Fuzzy AHP. The steps of this procedure is explained below:

**Step 1:** After the aggregation of the evaluations of $t$ DMs in one aggregate matrix based on geometric mean of preferences of $t$ DMs by applying Eq. 9, it is possible to employ the mean integration method to defuzzify the aggregated inputs in the decision matrix (i.e. transforming the fuzzy number $\tilde{A} = (l, m, u)$ into a form of crisp number) with an aim of checking the consistency of inputs (Kutlu & Ekmekçioğlu 2012) as follows:

$$P(\tilde{A}) = M = \frac{l+4m+u}{6} \quad (18)$$

**Step 2:** To evaluate the consistency of the comparison matrices at all levels of the hierarchical structure, it is possible by estimating the consistency index (CI) and the consistency ratio (CR) as mentioned previously in Eq. 2 and Eq. 3. The CR value should be maintained ≤ 10%. Nevertheless, the inputs of the matrix should be reviewed until the consistency is obtained.

**Step 3:** After performing the consistency test, modified Chang extent analysis method which includes the correction for Chang's normalization formula as proposed by Wang *et al.* (2008) can be applied. In this method, for every row in the aggregated matrix (Eq. 9), the row sum can be calculated by the following equation:

$$\widetilde{RS}_i = \sum_{j=1}^{n} \tilde{a}_{ij} = \left(\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} u_{ij}\right),\ i = 1,\ldots,n \quad (19)$$

The normalized row sum $\tilde{S}_i$ can be obtained by the following equation:

$$\tilde{S}_i = \frac{\widetilde{RS}_i}{\sum_{j=1}^{m} \widetilde{RS}_i} \tag{20}$$

$$= \left(\frac{\sum_{j=1}^{n} l_{ij}}{\sum_{j=1}^{n} l_{ij} + \sum_{k=1,k\neq i}^{n} \sum_{j=1}^{n} u_{kj}}, \frac{\sum_{j=1}^{n} m_{ij}}{\sum_{k=1,k\neq i}^{n} \sum_{j=1}^{n} m_{kj}}, \frac{\sum_{j=1}^{n} u_{ij}}{\sum_{j=1}^{n} u_{ij} + \sum_{k=1,k\neq i}^{n} \sum_{j=1}^{n} l_{kj}}\right)$$

$$= (l_i, m_i, u_i),\ i = 1,\ldots,n$$

**Step 4:** The crisp weights can be calculated by transforming the fuzzy weights (Calabrese *et al.* 2013) as follows:

$$w_i = S_i(\tilde{S}_i) = \frac{li + mi + ui}{3} \tag{21}$$

By means of normalization, the normalized crisp vector of weights is as follows:

$$W = (w_1^{'}, w_2^{'}, \ldots\ldots, w_n^{'}) \tag{22}$$

## 2.1.3.2 Sensitivity analysis of Fuzzy AHP technique

To examine the robustness and stability of outcomes that primarily depend on subjective evaluations of DMs, a sensitivity analysis is executed. The major aim is to assess how the range of variations in weights of main criteria of hierarchical structure impacts the ranking of alternatives. It is done by parametrically modifying the weights of one main criterion, while keeping fixed the relative proportions of all other main criteria (Tan *et al.* 2016) and so on for all other main criteria located below the overall goal of the hierarchical structure.

### 2.1.3.3 Comparative analysis between outcomes of AHP and Fuzzy AHP

This section displays the procedure of comparing and evaluating the differences in outcomes between traditional AHP **(Section 2.1.2)**, Fuzzy AHP and modified Fuzzy AHP **(Section 2.1.3)** with regard to: differences in priority weights of main criteria, evaluation criteria and alternatives, and differences in priority weights rankings. As mentioned previously, there are diverse methods to calculate priority weights in Fuzzy AHP by using different scales, and different aggregation techniques of preferences of DMs. A one Fuzzy AHP scale with three aggregation weight techniques (WAM1, WAM2 and WAM3) are used and the outcomes are compared with the outputs of two weights aggregation methods by traditional AHP (AHP-GMM and AHP-WAMM) as well as with the outputs of the modified Fuzzy AHP. Table 4 displays the different used techniques in this study.

**Table 4.** Compared methods of Fuzzy AHP and traditional AHP

| Short terminology | Proposed methodology |
|---|---|
| Technique 1: AHP-GMM | Traditional AHP-Geometric Mean Method **(Section 2.1.2)** |
| Technique 2: AHP-WAMM | Traditional AHP-Weighted Arithmetic Mean Method **(Section 2.1.2)** |
| Technique 3: FAHP-WAM1 | Fuzzy AHP-Weight Aggregation Method 1 **(Section 2.1.3)** |
| Technique 4: FAHP-WAM2 | Fuzzy AHP-Weight Aggregation Method 2**(Section 2.1.3)** |
| Technique 5: FAHP-WAM3 | Fuzzy AHP-Weight Aggregation Method 3**(Section 2.1.3)** |
| Technique 6: Modified FAHP | Modified Fuzzy AHP **(Section 2.1.3)** |

The convergence and divergence of outputs were tested for the three Fuzzy AHP techniques and the modified Fuzzy AHP with respect to the two traditional AHP techniques. The deviation of outputs is estimated by calculating the root mean square error (RMSE) (Lee 2015) according to the following formula:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - Y_i'\right)^2}{n}} \tag{23}$$

where $Y_i$ = priority weight produced by Fuzzy AHP or modified Fuzzy AHP, $Y_i'$= priority weight obtained from traditional AHP method, and $n$ = number of factors in the decision matrix.

Furthermore, the Spearman Correlation Coefficient ($R$) is used to evaluate the measure of association between ranks obtained by different techniques. This coefficient is frequently employed in relating the two ordinal characteristics and to evaluate the measure of association between ranks obtained by different techniques as pointed out by Li *et al.* (2012). The Spearman Correlation Coefficient can be defined as in the following equation (Kannan *et al.* 2014; Chitsaz & Banihabib 2015):

$$R = 1 - \frac{6\sum_{a=1}^{A} D_a^2}{A(A^2-1)} \tag{24}$$

where, $a$ = number of alternatives, $A$ = total number of alternatives, $D_a$ = the difference between the ranks obtained by different two approaches. In case the value of $R$ is equal to 1, it represents a perfect association between the ranks; $R$ is equal to zero, it means no association between the ranks; while in case $R$ is equal to -1, it represents a perfect disagreement between the ranks produced by two investigated approaches (Govindan *et al.* 2015).

### 2.1.4 Employing of Fuzzy AHP and Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (Fuzzy TOPSIS) techniques

In this methodology, an integrated methodology that combines Fuzzy Analytic Hierarchy Process (Fuzzy AHP) and Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (Fuzzy TOPSIS) is proposed to evaluate and prioritize a set of alternatives within a water loss management framework **(Section 2.1.1)**. The integration of Fuzzy AHP and Fuzzy TOPSIS methodology has proved itself adequate and effective in real applications in different disciplines (Gumus 2009; Samvedi *et al.* 2013; Tadic *et al.* 2013; Beskese *et al.* 2014; Taylan *et al.* 2014; Beikkhakhian *et al.* 2015; Tu & Chiu 2015). In addition to the wide application of this methodology, its feature of controlling, arranging, and decomposing the decision problem that is involving many attributes makes it more attractive than previously applied approaches in the field of water loss management.

The extent analysis Fuzzy AHP method which has been proposed by Chang (1996) and explained in details in **Section 2.1.3.1** has been used to develop the priority vector of weights of main criteria and evaluation criteria (i.e. the priority weights of decision elements in level 2 and level 3-Figure 8/**Section 2.1.1**). Furthermore, the three scenarios of aggregation of preferences of $t$ DMs as explained in details (Eq. 9-**Section 2.1.3.1**) with the aim of building the final pairwise comparison matrix have been used. The individual entries of decision matrices before the aggregation also employed the fuzzy scale illustrated in Table 3. The Fuzzy TOPSIS technique is used to aid in ranking of alternatives (Level 4-Figure 8/**Section 2.1.1**) in terms of their potential to meet the overall objective based on the evaluations and preferences of DMs. It is used to assign the performance of alternatives with respect to the evaluation criteria.

The integration of Fuzzy TOPSIS technique at this level is crucial in reducing the computational complexity and the amount of evaluations required from experts and DMs in comparison to Fuzzy AHP technique. As explained by Lima Junior *et al.* (2014) in case there is *n* alternatives and *m* evaluation criteria, there is a need for *m* judgments or evaluations for each alternative, while in Fuzzy AHP, the number of required evaluations for a decision matrix $A_{n*n} = n*((n-1)/2)$. Where *n* is the number of alternatives that will be evaluated with respect to a specific criterion. In our case we have 10 evaluation criteria in level 3-Figure 8, and 10 alternatives in level 4-Figure 8. Accordingly, the required evaluations in Fuzzy TOPSIS is 10 evaluations/alternative, while the required comparisons between the ten alternatives with respect to each evaluation criterion in Fuzzy AHP is 45 evaluations.

The TOPSIS method is a multiple criteria decision making technique proposed by Hwang and Yoon (1981) to identify a solution from a finite set of alternatives. Its principle based on the fact that, the chosen alternative should have the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution (Taylan *et al.* 2014; Beikkhakhian *et al.* 2015). Figure 12 below demonstrates the principle of TOPSIS method. The Fuzzy TOPSIS technique was proposed by Chen (2000) to solve multi-criteria decision making problems under fuzzy environment (Lima Junior *et al.* 2014) and to deal efficiently with uncertainty in the evaluations and judgments. By this technique, the alternatives have to be evaluated with respect to a set of criteria and as the linguistic experts' opinions are subjective, vague, and imprecise in nature (Islam *et al.* 2013), fuzzy set theory has to be used, and TFNs can be used to express the linguistic expert's opinions as shown below in Table 5.

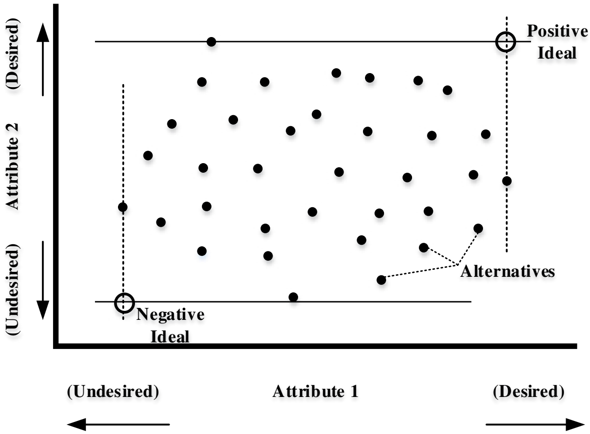



**Figure 12.** Illustration of principle of TOPSIS technique (adopted from Bayram and Şahin (2016)).

**Table 5.** Definition of linguistic evaluation (Ratings of alternatives with respect to evaluation criteria)

| Linguistic variables | Code | Positive TFN |
|---|---|---|
| Very Poor | VP | (1, 1, 1) |
| Poor | P | (1, 3, 5) |
| Fair | F | (3, 5, 7) |
| Good | G | (5, 7, 9) |
| Very Good | VG | (7, 9, 9) |

The steps of Fuzzy TOPSIS can be given as in the following:

**Step 1:** The importance weight of criteria $\widetilde{w}_j$ which describes the aggregated fuzzy weight of the $j^{th}$ criterion with respect to the overall goal, $C_j$ ($j$ = 1, …. , $n$), given by the $N^{th}$ DMs and calculated by Fuzzy AHP technique will fed to Fuzzy TOPSIS.

$$\widetilde{W} = [\widetilde{w}_1 \quad \widetilde{w}_2 \quad -- \ \widetilde{w}_j --\widetilde{w}_n] \tag{25}$$

**Step 2:** Aggregating ratings of alternatives: to build the decision matrix, the linguistic ratings of an alternative by different DMs expressed in terms of TFNs have to be aggregated. In case, there is $N$ DMs, and the rating of the $i^{th}$ alternative for $j^{th}$ criteria is $\widetilde{X}_{ij}$ = ($x_{ija}$, $x_{ijb}$, $x_{ijc}$), the aggregated rating can be expressed by the following equations:

$$x_{ija} = \frac{1}{N}\ [\,x_{ija}^{1} + x_{ija}^{2} + \cdots + x_{ija}^{N}] \tag{26}$$

$$x_{ijb} = \frac{1}{N}\ [\,x_{ijb}^{1} + x_{ijb}^{2} + \cdots + x_{ijb}^{N}] \tag{27}$$

$$x_{ijc} = \frac{1}{N}\ [\,x_{ijc}^{1} + x_{ijc}^{2} + \cdots + x_{ijc}^{N}] \tag{28}$$

**Step 3:** Building and normalizing the fuzzy decision matrix from the aggregated ratings of alternatives as follows:

$$\widetilde{DM} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & - & \tilde{x}_{1j} & - & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & - & \tilde{x}_{2j} & - & \tilde{x}_{2n} \\ - & - & - & - & - & - \\ \tilde{x}_{i1} & \tilde{x}_{i1} & - & \tilde{x}_{ij} & - & \tilde{x}_{in} \\ - & - & - & - & - & - \\ \tilde{x}_{m1} & \tilde{x}_{m2} & - & \tilde{x}_{mj} & - & \tilde{x}_{mn} \end{bmatrix} \tag{29}$$

where, $\tilde{X}_{ij}$ is the aggregated fuzzy rating of $i^{th}$ alternative with respect to $j^{th}$ criterion and, $i$ = 1, 2, 3, …,m, $j$ = 1, 2, 3,.., n.

The normalization of the decision matrix $\widetilde{DM}$ has to be carried out by the linear scale transformation as follows:

$$\widetilde{R} = [\tilde{r}_{ij}]_{m*n} \tag{30}$$

where, $\tilde{r}_{ij}$ is the normalized rating of the alternative, and the normalization has to be carried out by using the following equation:

$$\tilde{r}_{ij} = \left(\frac{Xija}{d_j^*}, \frac{Xijb}{d_j^*}, \frac{Xijc}{d_j^*}\right), d_j^* = \max(Xijc) \tag{31}$$

**Step 4:** The fuzzy weighted normalized decision matrix will be calculated by multiplying the weights of the evaluation criteria $\tilde{w}_j$ by the elements of the normalized fuzzy decision matrix $\tilde{r}_{ij}$ according to the following equations:

$$\tilde{V} = [\tilde{v}_{ij}]_{m*n} \tag{32}$$

$$\tilde{v}_{ij} = \tilde{r}_{ij} \otimes \tilde{w}_j \tag{33}$$

where, $i$ = 1, 2, 3, …,m, $j$ = 1, 2, 3,.., n, and the element of $\tilde{v}_{ij}$ is a normalized fuzzy number, and their elements are in the range of [0, 1].

**Step 5:** Defining the Fuzzy Positive Ideal Solution (FPIS, $A^+$), and the Fuzzy Negative Ideal Solution (FNIS, $A^-$): the positive ideal solution (PIS) allows maximizing the benefit attributes and minimizing the cost attributes. On the contrary, the negative ideal solution (NIS) does the opposite, by minimizing the benefit attributes and maximizing the cost attributes. The alternative which is closer to the PIS, and farther from the NIS is the leading solution (Islam *et al.* 2013; Lima Junior *et al.* 2014). The (FPIS, $A^+$) and (FNIS, $A^-$) can be defined according to the following equations:

$$A^+ = \{\tilde{v}_1^+, \tilde{v}_2^+, \tilde{v}_3^+ \ldots., \tilde{v}_j^+\} \tag{34}$$

$$A^- = \{\tilde{v}_1^-, \tilde{v}_2^-, \tilde{v}_3^- \ldots., \tilde{v}_j^-\} \tag{35}$$

where, $\tilde{v}_j^+$ = (1,1,1), and $\tilde{v}_j^-$ = (0,0,0)

**Step 6:** Computing the separation distances of each alternative from the FPIS and the FNIS to provide a measure of the closeness of the alternatives from the FPIS and the FNIS according to the following equations, which provide separation distance for two TFNs by the vertex method:

$$d(\tilde{v}_{ij}, \tilde{v}_j^+) = \sqrt{\frac{1}{3}[(\tilde{v}_{ija} - \tilde{v}_{ja}^+)^2 + (\tilde{v}_{ijb} - \tilde{v}_{jb}^+)^2 + (\tilde{v}_{ijc} - \tilde{v}_{jc}^+)^2]} \tag{36}$$

$$d(\tilde{v}_{ij}, \tilde{v}_j^-) = \sqrt{\frac{1}{3}[(\tilde{v}_{ija} - \tilde{v}_{ja}^-)^2 + (\tilde{v}_{ijb} - \tilde{v}_{jb}^-)^2 + (\tilde{v}_{ijc} - \tilde{v}_{jc}^-)^2]} \tag{37}$$

$$d_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^+), i = 1, 2, 3, \ldots, m \tag{38}$$

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-), i = 1, 2, 3, \ldots, m \tag{39}$$

**Step 7:** Computing the relative closeness coefficient ($CC_i$) of each alternative with respect to the (FPIS, $A^+$), and (FPIS, $A^-$) by using the following equation:

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-}, \; i = 1, 2, 3, \ldots, m \tag{40}$$

**Step 8:** Defining the ranking of the alternatives according to the values of closeness coefficients ($CC_s$), in descending order. The best alternative will be the closest to the FPIS and the farthest to the FNIS.

### 2.1.4.1 Sensitivity analysis of the Fuzzy AHP-Fuzzy TOPSIS technique

A sensitivity analysis is performed to analyze the behavior of alternatives when changes in the weights of criteria are imposed and to test the robustness of preference decisions (Guo & Zhao 2015). The concept of sensitivity analysis is to exchange the weight of each criterion produced by fuzzy AHP technique with another criterion weight (Önüt & Soner 2008; Gumus 2009). A number of combinations will be generated depending on the number of criteria, and each combination will stand as a new condition. The base condition represents the original outcomes. The $CC_s$ to the ideal solutions that state the ranking of alternatives will be calculated for each condition, and will be plotted to demonstrate the changes in these values associated with the changes in weights of criteria. Furthermore, the root mean square errors (RMSE) will be calculated for the produced CCs values in the new conditions/alternative with respect to the base condition by using the following equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - Y_i'\right)^2}{n}} \tag{41}$$

Where, $Y_i$ = CC value of alternative/new condition produced by Fuzzy TOPSIS and associated with the mutually exchange of weights of evaluation criteria produced by Fuzzy AHP, $Y_i'$ = CC value of alternative in the base condition, and $n$ = number of conditions where the evaluation criteria have been mutually exchanged their weights. Figure 13 illustrates the flowchart of the Fuzzy AHP-Fuzzy TOPSIS based multi criteria decision analysis framework for water loss management.

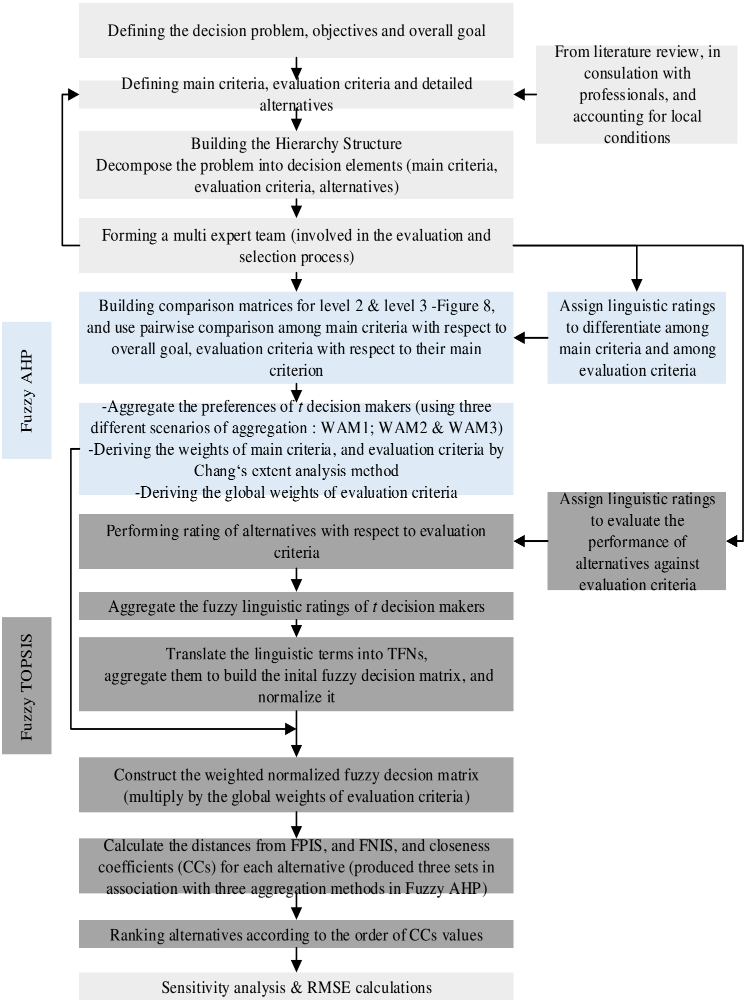



**Figure 13.** Flowchart of the Fuzzy AHP-Fuzzy TOPSIS based multi criteria decision analysis framework for water loss management.

## 2.2 Development of a simulation based multi-criteria decision making framework for the evaluation of water loss risk index in WSNs

### 2.2.1 Proposed water loss risk index (WLRI) framework

Due to insufficient financial resources and operational constraints such as the complexity and the extent of WSNs in the developing countries, there is a need to adopt gradual improvement plans for applying the optimum strategies of managing water losses. This entails the development of diagnostic tools to understand the conditions of different zones within WSNs and their criticality in terms of water losses and the associated environmental and social consequences. Accordingly, the application of potential strategies to manage water losses can be applied over zones with higher priority in terms of the previous issues. This approach will contribute in developing efficient operational and adequate monitoring programs over the whole WSNs. Furthermore, it promotes the practices of long term planning instead of local actions which are prevalent in most of the developing countries.

The proposed WLRI framework integrates the probability of water loss potential in a sub network and the possible consequences in terms of social and environmental impacts. It can be used to incorporate the potential of occurrence of water losses in networks as a result of different influential factors and the consequences, and can be defined in an interval from 0% to 100%. As it is well known, the vulnerability of WSNs to water losses is a consequence of numerous physical, operational and environmental factors (Friedl *et al.* 2012; Shafiqul Islam *et al.* 2012; Fuchs-Hanusch *et al.* 2013). Among these factors, the pressure in the system and the age of the pipes which increase the rate of leakage (Fares & Zayed 2009). The number of water meters, service connections, type of materials and demands are significantly influencing the rate of water losses (Tabesh *et al.* 2009). Traffic volumes influence the failure of pipes and the soil type influences the duration of leakage from pipes and the flow rates (Shafiqul Islam *et al.* 2012). For the consequences factors, they could include the population that might be affected (Kabir *et al.* 2015b), damage to surroundings and the type of serviced area (Fares & Zayed 2010).

In this context, for example, Morais *et al.* (2014) developed a model based on employing stochastic multi-criteria acceptability analysis method that helps water utilities to sort the areas within a water system based on their criticality in terms of water losses. This model addressed the problem at the zone level. It was limited to a small number of criteria (i.e. pressure, age of pipes, degree of interference, the quality of water, type of consumption and density of population supplied) with predefined thresholds to assist in categorizing the areas according to associated water loss indices. The previous criteria were categorized into technical, environmental and social aspects. The model considered and generalized the average values of criteria over the total area or zone (Morais *et al.* 2014). Otherwise, most of developed models are devoted to assess the performance and conditions of pipelines in WSNs (El Chanati *et al.* 2016). As pointed out by Fares and Zayed (2010), some of these models were limited to a very few factors that are contributing to water losses in WSNs. The others were so complicated so that water utilities were reluctant to depend on (Fares & Zayed 2010).

In the present work, the developed index in its significance is similar to the index that has been developed by Shafiqul Islam *et al.* (2012) to evaluate the water quality failure (WQF) potential in WSNs based on different causes factors and symptoms. The authors in this previously mentioned work developed a framework which includes the possible causes of failure of water quality in WSNs (i.e. turbidity and residual chlorine) and the symptoms as consequences to causes (i.e. taste and odor). They used this framework to categorize zones within WSNs according to the associated WQF values. The Fuzzy set theory was coupled with MCDM techniques, TOPSIS and ordered weighted averaging operator (OWA), to assess the WQF potential in WSNs.

In evaluation of risk of failure of water mains, Fares and Zayed (2010) developed a hierarchical fuzzy expert system. In this approach, the authors considered 16 risk factors and categorized them into four categories (i.e. physical, operational, environmental and post failure) to represent the potential and consequences of failures. A hierarchical fuzzy model consisting of four sub models, where each sub model corresponds to one main category, was developed. The relative weights of factors were collected through a questionnaire. The knowledge-based rules are considered to combine the outcomes of each sub model with the aim of producing an index that represents the risk of failure in each pipe (Fares & Zayed 2010). Another study conducted by Kabir *et al.* (2015b) which is based on the employment of a Bayesian Belief Network to evaluate the risk of failure of water mains. The study considered structural integrity index (i.e. diameter; age; length and thickness of pipe), water quality index (i.e. turbidity; water age and color of water), hydraulic capacity index (i.e. water pressure and velocity) and consequences factors (i.e. land use and population density).

In the present work, the identification of the most influential factors is based on: reviewing the available literature in this field, thorough discussions with actors from the responsible authorities who managed the water system under investigation and the scientific community in the region of the study. After preparing a comprehensive list of most common factors, the factors contributing to the development of the present study ware selected and identified from the comprehensive list based on their applicability to the scrutinized case study. Furthermore, it considers factors that have significance influence towards water losses in WSNs of the developing countries such as average supply hours, density of service connections and water meters. These factors are categorized according to their relevance and as followed by the previous explained studies. Figure 14 displays these factors. A detailed description about these factors is displayed in Table 6.

After building the WLRI framework, a hybrid methodology of fuzzy analytic hierarchy process (FAHP), fuzzy synthetic evaluation (FSE) technique and ordered weighted averaging (OWA) operator is proposed to evaluate the WLRI at pipe and zone levels in WSNs. The FAHP is introduced to evaluate the importance of elements of decision problem under group decision making environment, while FSE technique is introduced to build the membership functions of the basic factors, synthesizing their performances and defuzzifying the outputs to calculate the WLRI for each pipe. The OWA operator is employed to aggregate the individual WLRI/pipe for each group of pipes belongs to each zone in order to produce WLRI at zone level. Furthermore, Monte Carlo simulation model is incorporated to eliminate the limitations in the previous conventional approach. The intent is to assist water utilities mainly in the developing countries in arriving at a structured decisions on a scientific basis to diagnose the criticality of zones within WSNs according to the associated WLRI.

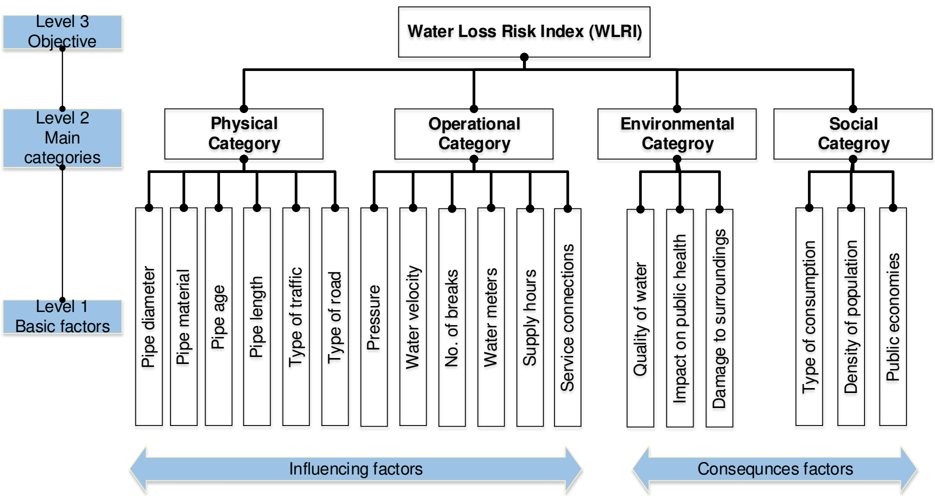



**Figure 14.** Hierarchical structure of contributing factors to water loss risk index (WLRI) in water distribution networks

**Table 6.** Contributing factors to water loss risk index (WLRI) in water distribution networks identified from previous studies

| Category | Factors | Description | References | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| Physical | | | | | | | | | | | | | | | | |
| | Pipe diameter (mm) | Pipes with larger diameters are less prone to failures than pipes with smaller diameters | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | | √ | | √ |
| | Pipe material | Different materials are failed in different ways | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | | √ | | √ |
| | Pipe age (year) | The effects of pipe degradation become more apparent over time | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | | √ | √ | √ |
| | Pipe length (m) | Pipes with larger lengths are more prone to failures than pipes with smaller lengths | | √ | | | √ | √ | √ | | √ | √ | | | | |
| | Type of traffic | The rates of failures increase proportionally with traffic loads | √ | √ | √ | | √ | | √ | √ | | √ | | | | √ |
| | Type of road | The condition of the road under which the pipe passes affects the rates of failure | √ | | | | √ | | | √ | | √ | | | | √ |
| Operational | | | | | | | | | | | | | | | | |
| | Pressure (m) | The changes in the internal pressure will change stress acting on the pipes | √ | √ | √ | √ | √ | | √ | | | √ | | √ | √ | √ |
| | Water Velocity (m/s) | High velocities corrode the internal walls of pipes | √ | √ | | √ | √ | | | | | √ | | √ | | √ |
| | No. of breaks (breaks/km/year) | High breakage rates indicate a poor condition of pipe lines | √ | √ | √ | | | √ | √ | | | √ | | | | |
| | Water meters (No.) | The increase of density of water meters indicates that, higher apparent losses are expected | | | | | | | | | | | √ | | | √ |
| | Average supply hours (hours/day) | The increase in the duration of water supply leads to less chances of pipe failure | | | | | | | √ | | | | √ | | | |
| | Service connections (No.) | The increase of density of water services indicates that, the risk of the pipe getting structurally worse is more | | | | | | | √ | | | | | | | √ |
| Environmental | | | | | | | | | | | | | | | | |
| | Quality of water | The degree of risk from contamination by infiltration | | √ | √ | √ | √ | | | √ | | √ | | √ | √ | |
| | Impact on public health (No. of illness) | The associated health risks from contaminated water and their effects on public safety | | √ | | | | | | | | | √ | | | |
| | Damage to surrounding | Potential property damage and traffic disruption | | √ | √ | | | | | | | | | | | |
| Social | | | | | | | | | | | | | | | | |
| | Type of consumption | The importance of the served category (i.e. residential, commercial, industrial) with high importance of residential category | √ | √ | √ | | | | | | √ | √ | | | √ | √ |
| | Density of population (No.) | The effect of failure is more critical in case there is high density of served people | | √ | | | √ | | √ | | | √ | | | √ | |
| | Public economies | This indicates the importance of served area, the importance is proportional with the increase in number of public economies | | | | | | | | | | | | | | |

**References: 1**= (Al-Barqawi & Zayed 2008); **2**= (Mohamed & Zayed 2013); **3**= (Fares & Zayed 2010); **4**= (Al-Barqawi & Zayed 2006); **5**= (Kabir *et al.* 2015b); **6**= (Kabir *et al.* 2015a); **7**= (Vairavamoorthy *et al.* 2007); **8**= (Yan & Vairavamoorthy 2003); **9**= (Kabir *et al.* 2015c); **10**= (El Chanati *et al.* 2016); **11**= (Khatri *et al.* 2012); **12**= (Best Practices 2003); **13**= (Morais *et al.* 2014); **14**= (Shafiqul Islam *et al.* 2012).

## 2.2.2 Employing of fuzzy analytic hierarchy process (FAHP)

The employing of FAHP intends to derive the relative importance of different decision elements that are displayed in Figure 14. In this step, four DMs provide pairwise comparison matrices for main categories and their factors. The modified Fuzzy AHP, which has been explained in details in **(Section 2.1.3.1),** is employed to determine the weights of main categories and their factors. The aggregation of evaluations of DMs, with an aim to establish the final pairwise comparison matrix, is performed by employing the geometric mean operator of individual evaluations. The used scale in the evaluation process is the same as the one used in Table 3–**Section 2.1.3.1.** More details about the inputs of DMs and the derivation of importance of factors are displayed in results section.

## 2.2.3 Fuzzy synthetic evaluation (FSE) technique

It is one of several fuzzy MCDA techniques in which an aggregated form is produced as a result of synthesizing various individual components of an evaluation (Khatri *et al.* 2012). This technique is widely used in quantifying multi-evaluations and multi-attribute such as program management (Hu *et al.* 2016), risk assessment of heavy metal pollution (Yang *et al.* 2016), risk assessment in green projects (Zhao *et al.* 2016), evaluation of risk factors in public-private partnership water supply projects (Ameyaw & Chan 2015) and so on. As a branch of fuzzy set theory, which offers an approach to explicit the fuzzy variables in mathematical logic, FSE technique can be employed to efficiently handle the imprecise non-numerical terms and takes into account the fuzziness in knowledge of experts that symbolizes risk assessment (Sadiq & Rodriguez 2004; Ameyaw & Chan 2015).

### 2.2.3.1 Fuzzification of the basic factors

As a requirement to employ the FSE technique in the evaluation of WLRI at pipe level in WSNs, there is a need to fuzzify the basic factors that are contributed to WLRI and available in the last level of the hierarchy structure of the decision problem as shown in Figure 14. The fuzzification requires the building of factors' membership functions which will be used to convert the field or real data into fuzzy numbers of values in an interval [0, 1]. To simplify the analysis, the membership functions have been classified into three levels (i.e. low, medium and high) and are represented by triangular membership functions. The low level indicates the lowest possible contribution to the WLRI. The medium level indicates the moderate contribution while the high level indicates the highest possible contribution to the WLRI. The derivation of membership functions for each factor is presented in the following paragraphs.

In the physical category, the size of the pipe is among the significant factors that contribute to the failure of water lines (Al-Barqawi & Zayed 2006, 2008). Fares and Zayed (2010) in their study of building expert system for risk of failure of water pipelines classified the pipe diameter factor into three sets where pipes with diameters less than 250 mm are considered as small, pipes with diameters between 250 mm to 500 mm as medium and pipes with diameters greater than 500 mm as large. Al-Barqawi and Zayed (2008) classified the pipe diameter attribute into five levels (i.e. less than 100 mm, 150-200 mm, 250-300 mm, 350-450 mm and greater or equal to 500 mm) according to its effect on water main condition, where the smallest diameters show less performance and the largest diameters show good performance. El Chanati *et al.* (2016) classified the pipe diameter attribute according to its effect on the performance of water pipelines into three classes (i.e. less performance for dimeters less than 200 mm, medium performance for diameters between 200 – 350 mm and high performance for diameters larger than 350 mm). In the present work, three categories of pipe diameters are considered to reflect their contribution towards WLRI in water pipelines: low contribution for pipe diameters more than 500 mm; medium contribution for pipe diameters between 200 mm to 500 mm and high contribution for pipe diameters less than 200 mm.

Tlili and Nafi (2012) in their study of developing a practical decision scheme to prioritize water pipe replacement developed a score scale from 0 to 10 to evaluate the criteria of pipes (i.e. age, material, breakage rate, etc.). For the pipe material factor, the best score of 10 was given for stainless steel, followed by steel with 6, High density polyethylene (HDPE) and Polyvinylchloride (PVC) with 4 and 0 for cast iron (CI). Marzouk *et al.* (2015) developed a score scale from 1 to 5 to represent the contribution of different factors in the pipe's deterioration. The value of 1 was assigned for the least contribution, while the value of 5 was assigned for the most contribution. The steel material was assigned a score of 2, while cast iron and asbestos were assigned a score of 4 and 5, respectively. Shafiqul Islam *et al.* (2012) assumed low contribution value for metallic pipes towards the leakage potential in networks (i.e. steel, ductile iron, galvanized iron, etc.), medium value for plastic pipes (HDPE, PE and PVC) and high values for other materials such as asbestos cement. Accordingly, we classified the metallic pipes, particularly steel and ductile iron, with low contribution to the rates of water losses, HDPE, PE and PVC with medium contribution, and cast iron and asbestos with high contribution.

For the pipe age factor, Marzouk *et al.* (2015) used the same score scale for pipe material and assigned a value of 1 for pipe age less than 20 years , and a value of 5 for pipe age more than 50 years. Kabir *et al.* (2015b) classified the effect of this factor into five categories (i.e. very low for pipe age less than 20 years, low for pipe age between 20 and 40 years, medium for pipe age between 40 and 60 years, high for pipe age between 60 and 80 years and very high for pipe age more than 80 years). In the present classification, this factor is classified into 3 categories: low for pipe age less than 20 years, medium for pipe age between 20 to 50 years and high for pipe age more than 50 years. The previous authors classified the effect of pipe length into five categories (i.e. very small for pipe length less than 25 meters, small for pipe length between 25 and 100 meters, medium for pipe length between 200 and 500 meters,, large for pipe length between 200 and 500 meters and very large for pipe length more than 500 meters. Accordingly, this factor is classified into three categories (i.e. low for pipe length less than 100 meters, medium for pipe length between 100 and 500 meters and high for pipe length more than 500 meters. Furthermore, the classification of traffic and type of road factors is based relatively on the classification adopted by Kabir *et al.* (2015b) and Al-Barqawi and Zayed (2008). They classified the type of traffic which indicates the average daily traffic into heavy, moderate and low, while they classified the type of road which indicates the condition of road to local, primary, secondary, freeway and arterial. In the present study, the type of road is classified as local, secondary and primary as the other types are not available in the region of the scrutinized case study.

In operational category, water pressure is considered as a representation of hydraulic capacity failure of pipes through inadequate pressure for firefighting purposes, inadequate flow to the customers and possible water losses by leakage (Rogers 2011). Al-Barqawi and Zayed (2008) classified the operational pressure attribute effect in evaluating the performance of water mains into three levels: low, moderate and high. Kabir *et al.* (2015b) classified the contribution of water pressure towards the risk of water mains failure into five performance measures: very low, ($-25$ m $\leq WP < -10$ m); low, ($-10$ m $\leq WP <$ 35 m); medium, (35 m $\leq WP <$ 70 m); high, (70 m $\leq WP <$ 120 m); very high, (120 m $\leq WP$). In the present work, the three categories were: low for pressure less than 35 m, medium for pressure between 35 m and 70 m and high for pressure more than 70 m. As the increase in water velocity increases the rate of internal corrosion of pipes, Kabir *et al.* (2015b) classified its effect into four categories (i.e. low for water velocity less than 0.2 m/s, medium for water velocity between 0.2 and 1 m/s, high for water velocity between 1 and 1.5 m/s and very high for water velocity more than 1.5 m/s. A nearly same classification is followed in the present work.

Al-Barqawi and Zayed (2008) classified the number of breaks factor in operation category into seven categories to evaluate its impact on water pipe condition. They used a scale from 0 to 10 where the best value is corresponded to 10. These categories are ranging from greater than 2 breaks/km/year which assigned a score of 0 and less than 0.05 breaks/km/year which assigned a score of 10. A nearly same approach was followed by Tlili and Nafi (2012) who classified this factor into six categories ranging from 0.05 breaks/km/year to more than 2.9 breaks/km/year. In the present work, this factor is classified into three categories (i.e. low for breakage rate less than 0.05 breaks/km/year, medium for breakage rate between 0.05 and 2 breaks/km/year and high for breakage rate more than 2 breaks/km/year. Shafiqul Islam *et al.* (2012) classified the contribution of density of water meters to leakage in pipes into three categories (i.e. low for water meters less than 30, medium for water meters between 30 and 60 and high for water meters between 30 and 100). The same classification was followed for the contribution of density of service connections. In the present work, a nearly same classification is followed as in the previous work. For supply hours factor, Khatri *et al.* (2012) in their study of computing the performance index for urban infrastructure systems classified this factor into four categories (i.e. excellent performance of system with more than 12 supply hours, good performance with 8 to 12 supply hours, satisfactory performance with 4 to 8 supply hours and poor performance with supply hours less than 4). The nearly same classification is followed in the present work.

In the environmental category, water quality index has been used as an indicator of presence of contaminants. El Chanati *et al.* (2016) classified the effect values of water quality factor into three levels: poor with high impurities level, fair with medium impurities level and good with low impurities level. In the present work, the same classification is considered but with different naming system (i.e. bad, good and excellent). Khatri *et al.* (2012) classified the impact on public health factor into four categories (i.e. excellent with nil incidents, good with 0 to 2 incidents, satisfactory with 2 to 4 incidents and poor with incidents more than 4). It is classified in the present work as it has low consequence with incidents less than 1, medium with incidents from 1 to 2 and high with incidents more than 2. Mohamed and Zayed (2013) classified the property damage into high impact, medium impact and low impact, while Fares and Zayed (2010) classified this factor into three groups according to the location of water losses, such as industrial, commercial or residential area. The high-medium-low impact classification is considered in the present work.

In the social category, the type of consumption or service has been used as an indicator of the importance of served area in terms of the affected customers due to failure of water pipes. Morais *et al.* (2014) classified this factor into four categories (i.e. domestic, commercial, agricultural and industrial). Herein, this factor is classified into three categories (i.e. domestic, commercial and industrial) with much importance is given to domestic category. The classification of population density factor is based nearly on the classification which has been followed by Morais *et al.* (2014). They classified this factor into three categories (i.e. low with population supplied less than 600 persons, medium with population supplied between 600 to 1200 persons and high with population supplied more than 1200 persons).

Table 7 displays the fuzzy sets of the basic factors that are contributed to WLRI. We benefited from the literature to identify the ranges of the performance levels and the thresholds associated with the basic factors.

**Table 7.** Characterization of the basic factors that are used to evaluate the WLRI (Fuzzy sets and impact thresholds)

| Performance measures (Main categories and basic factors) | | Impact levels | | |
|---|---|---|---|---|
| | | Low | Medium | High |
| Physical | | | | |
| | Pipe diameter (mm) | >500 | 200-500 | <200 |
| | Pipe material | Assumed for metallic | Assumed for plastic (HDPE; PE; PVC) | Cast iron, asbestos |
| | Pipe age (year) | <20 | 20-50 | >50 |
| | Pipe length (m) | <100 | 100-500 | >500 |
| | Type of traffic | Low | Moderate | High |
| | Type of road | Secondary | Local | Primary |
| Operational | | | | |
| | Pressure (m) | <35 | 35-70 | >70 |
| | Water Velocity (m/s) | <0.2 | 0.2-1.5 | >1.5 |
| | No. of breaks (breaks/km/year) | <0.05 | 0.05-2 | >2 |
| | Water meters (No.) | <30 | 30-60 | >60 |
| | Average supply hours (hours/day) | >12 | 4-12 | <4 |
| | Service connections (No.) | <30 | 30-60 | >60 |
| Environmental | | | | |
| | Quality of water | Excellent | Good | Bad |
| | Impact on public health (No. of illness) | <1 | 1-2 | >2 |
| | Damage to surrounding | Low | Moderate | High |
| Social | | | | |
| | Type of consumption | Industrial | Commercial | Residential |
| | Density of population (No.) | <500 | 500-1000 | >1000 |
| | Public economies (No.) | <1 | 1-2 | >2 |

Figure 15 shows an example of mapping the pipe diameter under the physical category–Figure 14, and its contribution to the WLRI. It shows the risk scale and membership functions for the previous basic factor and the derivation of three–tuple fuzzy set shown in Eq. 42 below for a pipe with a diameter of 300 mm.

$$A_i = [\mu_1, \mu_2, \mu_3] \quad (42)$$

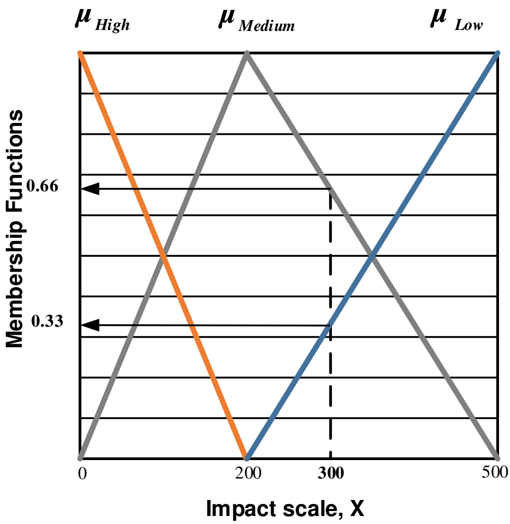



**Figure 15.** Membership functions and fuzzification of pipe diameter contributed to WLRI as an example.

The fuzzified three-tuple fuzzy set for this measurement can be obtained as a result of intersection between the value of the factor and the different membership functions. As illustrated in Figure 15, there is no intersection between this value and the high membership function (i.e., µHigh = 0). It intersects with the medium membership function at 0.67 (i.e., µMedium = 0.67) and it intersects with the low membership function at 0.33 (i.e., µLow = 0.33). This resulted a fuzzified value of [0.33, 0.67, 0.0], which indicates the contribution of this factor towrads WLRI in each range of high, medium and low contributions.

### 2.2.3.2 Aggregation of contributing factors to WLRI

The aggregation process depends on synthesizing the performances of lower level to the upper levels. The synthesized performance of basic factors at level 1-Figure 14 will provide the performance of main categories at level 2 (i.e., the synthesizing of perofmance of six basic factors that are belonging to physical category will produce the perfomance of physical category, and the same as for others). Subsequently, the synthesized perofmance of categories at level 2 will porduce the synthesized value of WLRI. At any level, the generated synethesized performance value will be in the form of three-tuple fuzzy set as in Eq. 42.

As pointed out by Khatri *et al.* (2012), the aggregation at any level is a result of multiplication of weights vector of factors (i.e., the weights vector of basic factors and main categories represents the local priority weights resulted from processing FAHP technique) by the evaluation matrix. As an example, if there is $n_j$ basic factors at level 1 that are belong to the main category $C_j$ at level 2, and after the fuzzification of the basic factors, the resulted evaluation matrix will be [$n_j$*3]. The vector of weights of $n_j$ basic factors resulted from FAHP technique will be $W_{jnj}$ = $[w_{j1}.........w_{ji}.....w_{jnj}]$, and the operation of aggregation will be as in the equations below:

$$C_j = W_{jnj} * A_{jnj} \tag{43}$$

$$C_j = [w_{j1}.........w_{ji}.....w_{jnj}] * \begin{bmatrix} \mu_1^{j1} & \mu_2^{j1} & \mu_3^{j1} \\ \dots & \dots & \dots \\ \mu_1^{ji} & \mu_2^{ji} & \mu_3^{ji} \\ \dots & \dots & \dots \\ \mu_1^{jnj} & \mu_2^{jnj} & \mu_3^{jnj} \end{bmatrix} \tag{44}$$

$$C_j = [\mu_1^j \quad \mu_2^j \quad \mu_3^j] \tag{45}$$

where $A_{jnj}$ represents the evaluation matrix produced by fuzzification of $n_j$ basic factors under a main category; $[\mu_1^{ji} \quad \mu_2^{ji} \quad \mu_3^{ji}]$ represents the three-tuple fuzzy set (i.e., low, medium, high) for a basic factor $i$ ($i$ = 1 to $n_j$), and $C_j$ represents the resulted three-tuple fuzzy set $[\mu_1^j \quad \mu_2^j \quad \mu_3^j]$ for a main category after the aggregation. The procedure will be followed for all levels to reach the fuzzy set of WLRI /pipe within a zone in WSN.

### 2.2.3.3 Defuzzification of the aggregated index

This step is concerned with converting the three-tuple fuzzy set, which rpresents the WLRI/pipe in the zone, to a crisp number. There are different methods to process the defuzzification such as, mean-max-membership operation, centroid method, maximum operator and others (Lu *et al.* 1999). The centroid method is one of the most used methods in which the finding of a point that represents the gravity center of the fuzzy set is required (Khatri *et al.* 2012). The equation below expalins the method:

$$C_A = \int_d^e \mu_A(x) x dx \ / \int_d^e \mu_A(x) \tag{46}$$

where $C_A$: centroid of the fuzzy set $A$ with interval from $d$ to $e$.

In this work, the defuzzification will be done at level 3, where the defuzzified outcome will represent the WLRI for the pipe. To represent the WLRI in each pipe, three levels of membership functions are proposed, the centroid values will be deemed as follows:

$$\text{WLRI/pipe}_i = [B_i]*[C]^T \tag{47}$$

where WLRI/pipe$_i$ is the defuzzified value of WLRI for pipe i, $B_i$ is the value of WLRI for pipe i in the form of three –tuple fuzzy set, and $[C]^T$ is the transpose of centroid values vector of the proposed membership functions, C = [$C_{low}$, $C_{Medium}$, $C_{High}$].

## 2.2.4 Employing of Ordered weighted averaging (OWA) operator

The OWA operator is proposed by Yager (1988) and concerned with the problem of aggregating criteria functions to form an overall decision function (Yager 1988). The weights in OWA are attached to ordered objective functions, which are different to the weighted sum approach in which a specific weight is assigned to each objective function (Chassein & Goerigk 2015). In reference to Yager (1988), the OWA operator of dimension $n$ is a mapping function $F: R^n \rightarrow R$ , where $n$

represents the number of attributes which have an associated weighting vector $W = [w_1, w_2, \ldots, w_n]^T$ such that:

$$\sum_{i=1}^{i=n} w_i = 1; \quad 0 \leq w_i \leq 1 \tag{48}$$

The mapping function can be calculated as follow:

$$f(a_1, a_2, \ldots, a_n) = \sum_{j=1}^{n} w_j b_j \tag{49}$$

where $b_j$ is the $j$th largest element of the collection of the aggregated objects ($a_1, a_2, \ldots, a_n$), which in our case represent the values of WLRI for pipes within a zone.

A primary characteristic of this operator is the re-ordering, i.e. sorting the input data in descending order (Mohammed *et al.* 2016). The determination of OWA operator associated weights is a key issue and numerous studies have been performed in this regard. In the present work, we employed two new developed methods proposed by Wang *et al.* (2015) and Mohammed *et al.* (2016), respectively. The most robust method has to be adopted for further analysis.

#### 2.2.4.1 Ordered visibility graph weighted averaging (OVGWA) aggregation operator

In this method, an ordered visible graph method based on visibility graph is developed to convert the ordered data to a network. Subsequently, a model of random walks is employed to estimate for each node the arriving probability. The associated weights will be determined based on the arriving probabilities which are appeared in the ordered visibility graph (Wang *et al.* 2015).

As pointed out by Wang *et al.* (2015), in case there is a set of ordered data $O = \{o_1, o_2, o_3, \ldots, o_j, \ldots, o_n\}$, where $o_j$ is the $j$th largest element of the set and the coordinate ($j$, $o_j$) represents the ordered value $o_j$ and its order $j$. The visibility criteria of the ordered visibility graph is similar to visibility graph and can be assigned as follows: for two data values ($i$, $o_i$) and ($j$, $o_j$) that have visibility if any other value ($k$, $o_k$) is placed between them fulfills the below condition:

$$o_k < o_j + (o_i - o_j)\frac{j-k}{j-i} \tag{50}$$

In case an ordered visibility graph with $n$ nodes, the link can be represented by adjacency matrix $A$ whose element $A_{ij}$ = 1(0) if there is a link from $i$ to $j$. The degree of node $i$ is denoted by $K_i$ and given by $K_i = \sum_j A_{ij}$. As defined by Noh and Rieger (2004), the rule of the transition probabilities is: A walker at node $i$ and time $t$ chooses one of its $K_i$ neighbors with equal probability to which it hops at time $t$+1, so the transition probability from node $i$ to node $j$ is $A_{ij}/K_i$. The probability $P_i$ to detect the walker at node $i$ is stationary distributed when the time is infinite. The stationary solution is calculated as below:

$$P_i^{\infty} = \frac{Ki}{\mathcal{N}} \tag{51}$$

where $\mathcal{N} = \sum_i K_i$.

For each node in the ordered visibility graph, the arriving probability was utilized as the associated OWA operator weight of the corresponding ordered data set. The following steps summarize the application of OVGWA for a set of values with *n* data values which will have *n* nodes in the corresponding ordered visibility graph.

The OVGWA operator is a mapping $F: I^n \rightarrow I,\ I \in R$, where:

$$F\,(a_1, a_2, \ldots, a_n) = w_1 a_1 + w_2 a_2 + w_3 a_3 + \ldots + w_n a_n \quad (52)$$

where $a_i$ is the *i*th value in a collection of aggregated objects, and $w_i$ represents corresponding weight of $a_i$ value and satisfies: $\sum_{i=1}^{i=n} w_i = 1$; $w_i \in [0, 1]$. The weight $w_i$ can be calculated by employing Equation 51 which can be redefined as below:

$$w\mathrm{i} = \frac{Ki}{\mathcal{N}} \quad (53)$$

where $K_i$ is the degree of node *i* and $\mathcal{N} = \sum_i K_i$ .

### 2.2.4.2 Ordered weighted averaging operator based on Laplace distribution (OWALD)

This type of OWA operators is proposed by Mohammed *et al.* (2016) and applied to the issue of classification of breast tumor. It is utilizing the Laplace distribution to estimate the vector of associated weights of OWA operator. The vector of weights $W_i$ of the OWA operator is stated as below:

$$wi\ = \frac{1}{2\lambda_n} e^{-\frac{|i-\theta_n|}{\lambda_n}} \quad (54)$$

where *n* is the number of aggregated attributes, $\lambda_n$ is the scale of the Laplace distribution (Kotz *et al.* 2000), $\theta_n$ is the mean of the number of attributes.

$$\theta_n = \frac{1}{n}\ \frac{n\,(1+n)}{2} = \frac{1+n}{2} \quad (55)$$

The standard deviation of the Laplace distribution $\sigma$ can be calculated as follows:

$$\sigma = \sqrt{2}\,\lambda = \sqrt{\frac{1}{n}\sum_{i=1}^{i=n}(i-\theta_n)^2} \quad (56)$$

To fulfill the condition that the sum of all weights should equal 1, Eq. (54) have to be redefine as follows:

$$wi = \frac{\frac{1}{2\lambda_n} e^{-\frac{|i-\theta_n|}{\lambda_n}}}{\sum_{i=1}^{i=n} \frac{1}{2\lambda_n} e^{-\frac{|i-\theta_n|}{\lambda_n}}} \quad (57)$$

By substituting the parameter $\theta_n$ , Eq. (57) can be rewrite as follows:

$$wi = \frac{\frac{1}{2\lambda_n} e^{-\frac{\left|i - \frac{1+n}{2}\right|}{\lambda_n}}}{\sum_{i=1}^{i=n} \frac{1}{2\lambda_n} e^{-\frac{\left|i - \frac{1+n}{2}\right|}{\lambda_n}}} \tag{58}$$

The Laplace distribution is characterized by its stability and robustness towards outliers (Kotz *et al.* 2012). As previously mentioned in section 2.2.4.1, after the calculation of associated weights for each value of WLRI/pipe, it is possible to apply Eq. 49 which represents the WLRI/zone.

## 2.2.5 Scenario analysis

It is a type of sensitivity analysis, which can be used to provide knowledge about the relevance between the inputs and outputs of the model. In this work, the concept of scenario analysis was related to exchanging the weight of each criterion in level 2, Figure 14 produced by Fuzzy AHP technique with another criterion weight in the same level (Gumus 2009; Zyoud *et al.* 2016a) and by assigning equal weights to all criteria located in level 2, Figure 14. Depending on the number of criteria, a number of combinations will be produced where each combination will stand as a new scenario. The WLRI/zone is calculated in association with each scenario while the original outcomes of WLRI/zone level was considered as a base condition. The root mean square errors (RMSE) is evaluated for the generated WLRI values at zone level in the new scenarios with respect to the base condition using the following equation:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(X_i - X_i')^2}{n}} \tag{59}$$

where, $X_i$ = WLRI/new condition produced in association with the mutually exchange of weights of criteria produced by FAHP or as a result of equal weights of criteria, $X_i'$= WLRI value in the base condition, and $n$ = number of conditions where the criteria have been mutually exchanged their weights or having the same weights. The results was compared for the two aggregating methods, OVGWA and OWALD.

## 2.2.6 Monte Carlo simulation model

For the method with least RMSE from **Section 2.2.5**, OVGWA or OWALD, a Monte Carlo simulation analysis is integrated in the decision analysis model to examine how the changes in relative weights of main categories and basic factors can affect the values of WLRI at zone level. This simulation enables to incorporate probabilistic functions to eliminate the limitations of deterministic and fuzzy group decision making (Bayram & Şahin 2016). Sari (2013) incorporated Monte Carlo simulation analysis in a two-step Fuzzy AHP and Fuzzy TOPSIS model to analyze the sensitivity of the selected option to the relative weights of evaluation criteria. Bayram and Şahin (2016) integrated a simulation technique with TOPSIS method to acquire a better insight over options' preference structure. In the present model, a random weight vector of crisp values is generated using the triangular probability distribution function with triangular numbers that were created by using Eq. 20 (the outputs of this equation represent the fuzzy weight of elements of the Fuzzy AHP method). As explained by Bayram and Şahin (2016), if the $v_j^t$ represents the random weight of a decision element drawn from a triangular distribution in $t^{\text{th}}$ iteration, the random vector of weights $V^t[v_1^t, \dots\dots, v_{j,}^t \dots\dots, v_n^t]$ can be obtained as explained in Eq. (60) below for the triangular distribution probability density function shown in Figure 16:

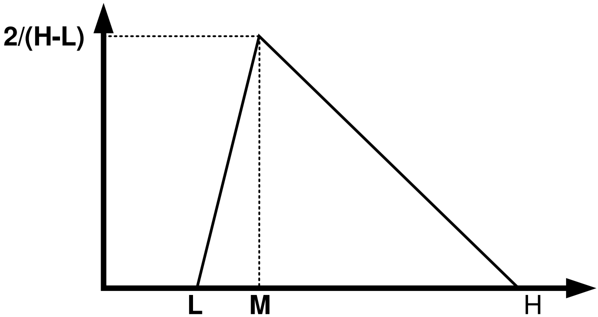



**Figure 16.** Triangular distribution probability density function.

$$T = \begin{cases} L + \sqrt{U(H-L)(M-L)}; & \text{if } U < \dfrac{M-L}{H-L} \\ H - \sqrt{(1-U)(H-L)(H-M)}; & \text{if } U > \dfrac{M-L}{H-L} \end{cases} \quad (60)$$

where, *U* is a uniform random number in an interval (0, 1) and *T* is a random number drawn from the triangular distribution.

For the normalization of the vector of weights, it is possible to neglect this step as it does not have any impact on the final ranking of zones generated by simulation model in terms of their WLRI values. In turn, this will reduce the required running time of the used algorithm (Bayram & Şahin 2016). Figure 17 illustrates the Flowchart of the proposed methodology to evaluate the WLRI at pipe and zone levels in WSNs.

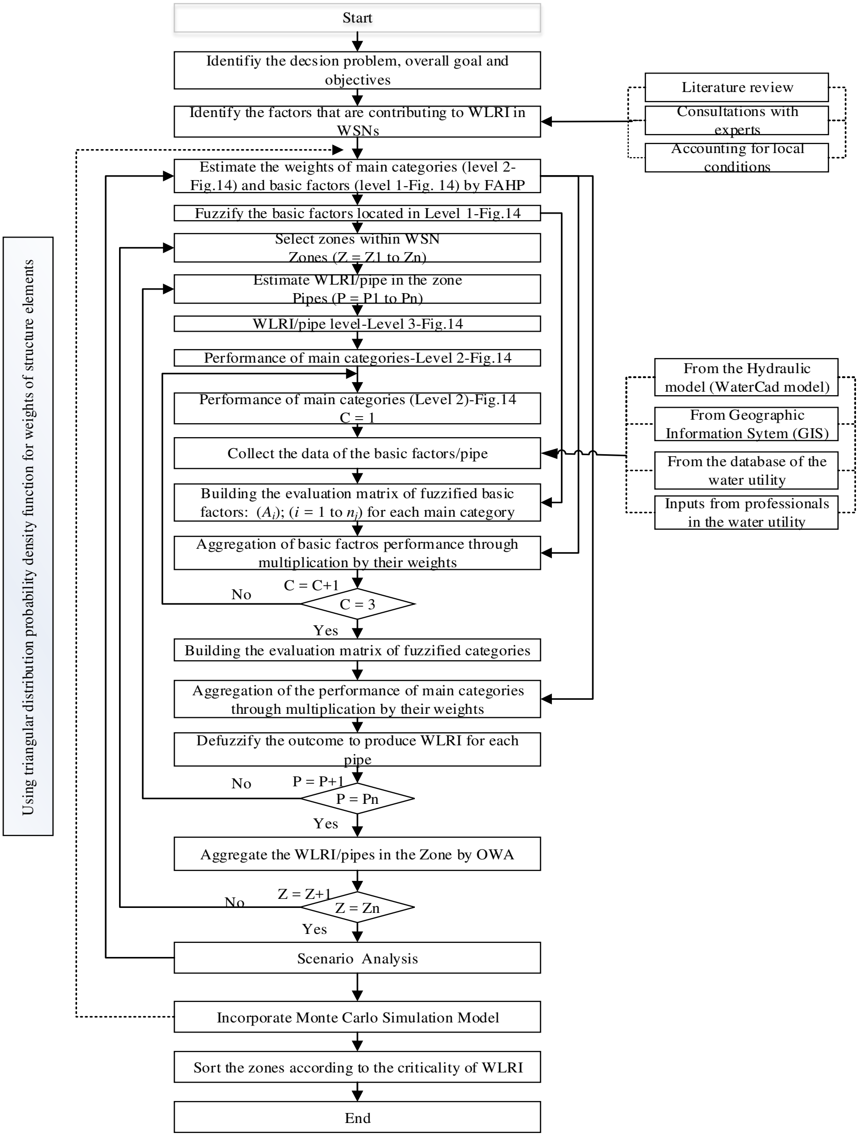



**Figure 17.** Flowchart of the proposed methodology to evaluate the WLRI at pipe and zone levels in WSNs.

# 3 Case study[3]

The proposed methodologies were applied to Nablus Water Distribution System (NWDS), Nablus City-Palestine to prioritize a set of strategies that have been proposed as potential alternatives to manage water losses in water supply systems of developing countries. Furthermore, they are applied to recognize the criticality of zones within these water supply systems according to water losses indices. The NWDS represents a typical-developing country water distribution system. In Palestine, the poor conditions of water distribution networks, the high levels of water losses which are up to about 50% of the total input to the system, the intermittent supply scheme of operation due to water shortage and unstructured systems are the major deficiencies that marked water distribution systems in this region (Mimi *et al.* 2004; Abu-Madi & Trifunovic 2013). The average of water losses in NWDS was about 38% of the total input to the system in year 2012 with values in some zones that were high as 51% (WSSD 2009). The estimations of NRW for NWDS for the year 2014 have shown a monthly NRW ranges from 35% to 44%. This previous figure was obtained based on available data of water balance generated on monthly basis by water utility of Nablus municipality.

The population of Nablus city is nearly 150,000 (PCBS 2015). The NWDS was set in place by 1932 and has been broadened to a present length of 290 km of water distribution lines that have diameters with ranges from 50 mm to 300 mm. The scanty definition of well-structured pressure zones in association with adopting intermittent model of operation causes broad portions of the water system to be under the effects of high pressures and to witness high events of water hammer and transient flows. As a result of these stresses, NWDS is experiencing high rates of pipe bursts and failures of domestic water meters. The existing sources are failed to meet the increasing demands, which in turn raising the operational problems. The response to the previous challenges was manifested by introducing more and more new interconnections of pipe networks, increasing the operational pressure in the system and employing the periodic supply of water to the different parts of the system. The adoption of these unsustainable policies have exacerbated the problem. This is clear by boosting the already severe leakage problems as a consequence of high pressures. These high pressures mainly resulted from the introducing of complicated models of operation such as intermittent mode which aimed to supply the customers within a specific zone by their needs of water during a limited period of time (WSSD 2009).

In general, water utilities in Palestine are struggling to reduce the high levels of water losses in their systems. They are aware about the significance of investing in the recovered water to compensate the existing gaps between the available water supplies and the growing in required demands. Furthermore, the different implications (i.e. social, health and environmental dimensions) associated with water losses management imply the consideration of them in addition to the economic costs and benefits associated with this decision problem. As explained previously, the involvement of the most concerned and influential actors in this process is a substantial objective to arrive at sustainable solutions. The inclusion of preferences of stakeholders on the various objectives related to water loss management has been a focal feature in this work. It plays a prime role in formulating sustainable strategies for water loss management as the consensus resulted from integrating the objectives of stakeholders towards this decision making problem is seen as an aspect of sustainability. Furthermore, it facilitates deep insight into the decision problem and improves the learning and exploration through interactive discussions and group decision making.

[3] Parts of this chapter have been published in (Zyoud *et al.* 2016a; Zyoud *et al.* 2016b; Zyoud & Fuchs-Hanusch 2017a).

For the evaluation of the developed water loss management framework (Zyoud *et al.* 2016b), four groups of experts and DMs who have an in-depth understanding of the decision problem are participated in the process of evaluating the general developed framework and in incorporating their concerns, interests and preferences to nominate the most appropriate strategy in controlling and managing water losses in NWDS. They are induced to assess the developed framework with an aim of building a robust and efficient framework. The first and second groups demonstrated by representatives from Economic and Tariff Department (Group 1-DM1), and Water Control Directorate (Group 2-DM2) at Palestinian Water Authority (PWA), respectively. The PWA has overall responsibility in managing water resources and wastewater sector in Palestine, and it is responsible in issuing the general policy, plans and strategies (PWA 2016). The third group represented the interests of environmental groups and demonstrated by the Palestinian Hydrology Group for Water and Environmental Resources Development (PHG) (Group 3-DM3). This group is the major non-governmental organization in Palestine which is working in improving the access to water service and sanitation (PHG 2016). The last group represented the interests of the operator of the water systems (Group 4-DM4) and demonstrated by actors from Water Supply and Sanitation Department (WSSD) at Nablus municipality, Palestine. This department renders two vital services: water supply and sanitation, and serves more than 160000 inhabitants of Nablus city and the surrounding villages. It is managed by a total number of 289 employees (Municipality 2016).

The researcher was responsible for the decision–aid procedure with an aim to come up with a clear decision problem definition agreed upon by all DMs. In this stage, the DMs are involved in evaluating the elements of the hierarchy structure of the decision problem. This step is followed by designing a survey form to collect the preferences and evaluations of DMs towards the decision problem elements based on the requirement of AHP technique which has been explained in details in **Section 2.1.2** and Zyoud *et al.* (2016b). The survey defines the objectives, explains the AHP procedure in eliciting the required evaluations by supporting example and builds the required decision matrices at each level of the developed framework to help DMS in incorporating their evaluations in these matrices. A sample of the distributed survey is displayed in **Appendix A**. The completion of surveys was carried out after a thorough discussions among each group of DMs to reach consensus evaluations that represent the concerns and interests of each group. The completed surveys were analyzed by the researcher. They are checked for their consistencies. The inconsistent evaluations are improved based on employing the AHP calculator (BPMSG 2015) as explained in details in Zyoud *et al.* (2016b). The DMs are requested to revise their evaluations after the improving of inconsistent evaluations. Afterwards, the AHP procedure in deriving the priority weights of different elements of decision making problem is followed as explained in Zyoud *et al.* (2016b).

In the same context of developing a reliable strategic water loss management decisions (Zyoud *et al.* 2016a), an integrated methodology of Fuzzy AHP and Fuzzy TOPSIS is further employed. The evaluations of three groups of DMs among the main criteria and evaluation criteria are obtained based on Fuzzy AHP methodology, while Fuzzy TOPISIS technique is followed to aid in the ranking of alternatives in terms of their potential to meet the overall objectives. The first and second groups ((Group 1-DM1) and (Group 2-DM2)) in addition to (Group 4-DM4) (herein indicated as Group 3-DM3) who are participated in the work demonstrated in Zyoud *et al.* (2016b) are involved in this work. A survey that defines the major objectives of the work and explains step by step the requirements of the integrated methodology with supporting examples is designed to help DMs in incorporating their evaluations among the different elements of the decision problem. A sample of the distributed survey is displayed in **Appendix B**.

For the development of a hybrid framework to assess the WLRI in selected zones within NWDS, four experts were enrolled in this work to evaluate the importance of factors that contribute to water losses. Two experts out of four have been nominated from WSSD at Nablus municipality. The first expert represents the interests of research and studies division at WSSD, while the second expert represents the interests and concerns of water loss reduction unit at this department. The other two experts have been nominated from the academic and scientific community who have a wide knowledge of NWDS and have active participations in programs devoted to manage water losses in NWDS. An evaluation form was developed and send to the team of experts after a thorough discussion about the considered factors. More details can be found in **Appendix C.**

The data of the basic factors that are required to evaluate the WLRI in zones has been collected from different sources. The hydraulic model of NWDS and the Geographic Information System (GIS) model were the source of most of pipe attributes (i.e., pipe diameter, pipe material, pipe age, pipe length, pressure, velocity in the pipes and average supply hours). For other basic factors, the database of WSSD and the inputs of professionals in WSSD have been used to source the required data. The database of the project named: Hydraulic Analysis Study of the Nablus Water Supply System is used also as a source of data, such as the use of population density plans to identify the density of served customers. For the pressure attribute in pipes, the pipe average pressure is considered by taking the average of its two corresponding nodal pressures. The lack of precise data pertaining to some factors (i.e. no. of breaks, quality of water, no. of illness and damage to surroundings) in most cases has led to assuming values of these factors in the low effect limits or average as in case of water quality. Missing information related to other factors in some cases is collected from water utility experts. Ten zones out of thirty zones within NWDS have been selected to test the applicability of the developed model. These zones have been nominated as the data of detailed water balance calculations, NRW calculations and minimum nigh flow (MNF) analyses are available for these zones from a periodic technical report prepared by water loss reduction unit at WSSD. For the examined zones in this study, the codes of these zones and their water losses as an output of water balance calculations are (NW3: 44.9%, SE2: 41.4%, SE1: 41.1%, S3: 34.3%, S5: 24.8%, NW0: 35.4%, W0: 27.4%, W3: 18.9%, W1: 22.7% and W2a: 11.2%). Figure 18 illustrates the layout of different zones in NWDN and the selected zones. Table 8 displays a sample of collected data for Zone NW0-NWDS.

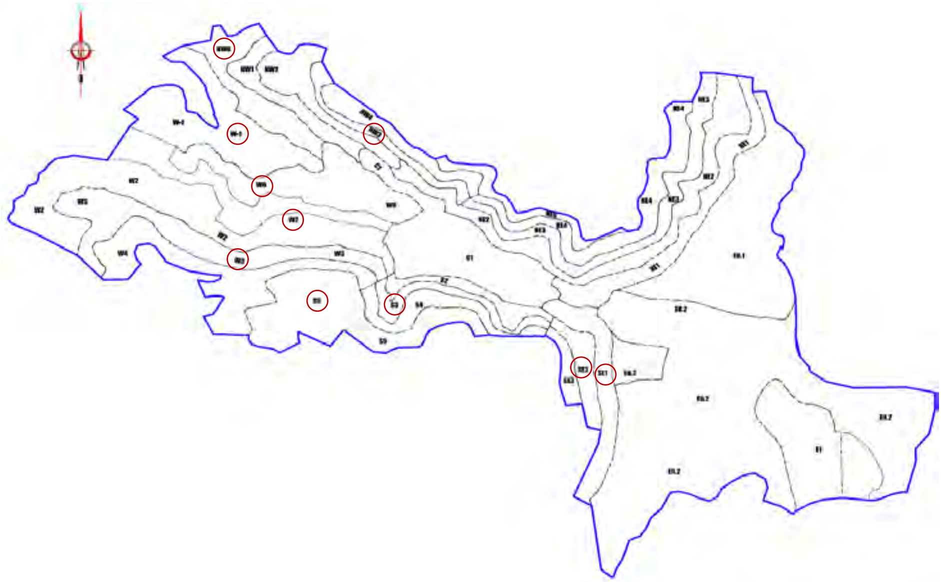


**Figure 18.** Illustration of different zones of NWDN and the selected zones, **Source (WSSD 2009)**.

**Table 8.** Data of basic factors of Zone NW0-NWDS

| Pipe ID | Pipe Diameter (mm) | Pipe Material (type) | Pipe Age (years) | Pipe Length (m) | Type of Traffic (type) | Type of Road (type) | Pressure (m) | Water Velocity (m/s) | No. of breaks(no./km/year) | Water Meters (no.) | Supply hours (no.) | Service connections (no.) | Quality of water (type) | No. of illness (no.) | Damage (type) | Type of consumption (type) | Density of population (no.) | Public economies (no.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1868 | 150 | Steel | 5 | 213.31 | moderate | local | 42 | 0.1 | 0 | 30 | 6 | 19 | good | 0 | low | residential | 150 | 0 |
| 12 | 100 | Galvanized steel | 17 | 444.01 | heavy | local | 51 | 0.22 | 1 | 51 | 6 | 31 | good | 0 | low | residential | 255 | 0 |
| 1869 | 150 | Steel | 5 | 73.12 | moderate | local | 50 | 0.41 | 0 | 9 | 6 | 6 | good | 0 | low | residential | 45 | 0 |
| 1849 | 100 | Galvanized steel | 17 | 145.6 | moderate | local | 44 | 0.64 | 0 | 18 | 6 | 11 | good | 0 | low | residential | 90 | 0 |
| 3153 | 75 | Galvanized steel | 19 | 24.75 | moderate | local | 45 | 1.3 | 0 | 5 | 6 | 2 | good | 0 | low | residential | 25 | 0 |
| 1257 | 100 | Galvanized steel | 17 | 273.62 | moderate | local | 38 | 0.09 | 0 | 35 | 6 | 18 | good | 0 | low | residential | 175 | 0 |
| 9 | 110 | HDPE | 10 | 345.01 | moderate | local | 68 | 0.08 | 0 | 50 | 6 | 27 | good | 0 | low | residential | 250 | 1 |
| 6 | 110 | HDPE | 10 | 164.81 | moderate | local | 67 | 0.15 | 1 | 19 | 6 | 11 | good | 0 | low | residential | 95 | 0 |
| 3132 | 150 | Steel | 5 | 62.88 | moderate | local | 36 | 1.17 | 0 | 6 | 6 | 3 | good | 0 | low | residential | 30 | 0 |
| 1870 | 150 | Steel | 5 | 229.72 | moderate | local | 45 | 0.2 | 0 | 31 | 6 | 17 | good | 0 | low | residential | 155 | 0 |
| 3162 | 75 | Galvanized steel | 17 | 47.64 | moderate | secondary | 50 | 2.12 | 0 | 8 | 6 | 5 | good | 0 | low | residential | 40 | 0 |
| 2 | 150 | Steel | 5 | 203.51 | moderate | local | 35 | 1.38 | 0 | 26 | 6 | 15 | good | 0 | low | residential | 130 | 0 |
| 1867 | 75 | Galvanized steel | 11 | 177.37 | moderate | local | 36 | 0.23 | 0 | 25 | 6 | 14 | good | 0 | low | residential | 125 | 0 |
| 10 | 75 | Galvanized steel | 11 | 23.81 | moderate | local | 30 | 0.07 | 0 | 5 | 6 | 3 | good | 0 | low | residential | 25 | 0 |
| 11 | 100 | Galvanized steel | 17 | 283.3 | heavy | local | 34 | 0.31 | 0 | 40 | 6 | 23 | good | 0 | low | residential | 200 | 2 |
| 3131 | 150 | Steel | 5 | 183.98 | moderate | local | 47 | 1.13 | 0 | 27 | 6 | 20 | good | 0 | low | commercial | 135 | 0 |
| 1852 | 50 | Galvanized steel | 43 | 188.27 | moderate | local | 45 | 0.37 | 0 | 26 | 6 | 15 | good | 0 | low | residential | 130 | 0 |
| 3161 | 50 | Galvanized steel | 43 | 95.11 | moderate | local | 73 | 0.37 | 0 | 13 | 6 | 8 | good | 0 | low | residential | 65 | 0 |
| 492 | 50 | Galvanized steel | 43 | 10.28 | moderate | local | 37 | 0.37 | 0 | 3 | 6 | 2 | good | 0 | low | residential | 15 | 0 |
| 493 | 50 | Galvanized steel | 43 | 12.74 | moderate | local | 39 | 0.37 | 0 | 3 | 6 | 3 | good | 0 | low | residential | 15 | 0 |
| 8 | 100 | Galvanized steel | 17 | 31.12 | moderate | local | 41 | 0.46 | 0 | 5 | 6 | 4 | good | 0 | low | residential | 25 | 0 |
| 3565 | 350 | Steel | 5 | 1379.93 | heavy | primary | 129 | 0.49 | 1 | 0 | 6 | 0 | good | 0 | low | residential | 0 | 0 |
| 3156 | 150 | Steel | 5 | 159.9 | moderate | local | 56 | 1.02 | 0 | 25 | 6 | 13 | good | 0 | low | residential | 125 | 0 |
| 3157 | 150 | Steel | 5 | 143.59 | moderate | local | 53 | 0.98 | 0 | 18 | 6 | 11 | good | 0 | low | residential | 90 | 0 |
| 3165 | 75 | Galvanized steel | 17 | 57.1 | moderate | local | 48 | 1.95 | 0 | 8 | 6 | 6 | good | 0 | low | residential | 40 | 0 |
| 3168 | 100 | Galvanized steel | 17 | 28.78 | moderate | local | 63 | 0.27 | 0 | 5 | 6 | 3 | good | 0 | low | residential | 25 | 0 |
| 3130 | 200 | Steel | 5 | 126.3 | heavy | primary | 68 | 0.8 | 0 | 17 | 6 | 9 | good | 0 | low | residential | 85 | 0 |
| 3160 | 50 | Galvanized steel | 9 | 59.61 | moderate | secondary | 66 | 0.73 | 0 | 9 | 6 | 5 | good | 0 | low | residential | 45 | 0 |
| 3169 | 100 | Galvanized steel | 17 | 129.59 | moderate | local | 54 | 0.37 | 0 | 20 | 6 | 11 | good | 0 | low | residential | 100 | 0 |
| 5 | 110 | HDPE | 10 | 313.03 | moderate | local | 65 | 0.05 | 0 | 45 | 6 | 23 | good | 0 | low | residential | 225 | 2 |
| 13 | 100 | Galvanized steel | 17 | 696.74 | moderate | local | 34 | 0.4 | 1 | 87 | 6 | 45 | good | 0 | low | residential | 435 | 0 |
| 1238 | 100 | Galvanized steel | 17 | 33.99 | moderate | local | 39 | 0.09 | 0 | 6 | 6 | 4 | good | 0 | low | residential | 30 | 0 |
| 3164 | 75 | Galvanized steel | 17 | 81.74 | moderate | local | 47 | 1.79 | 0 | 11 | 6 | 7 | good | 0 | low | residential | 55 | 0 |
| 997 | 110 | HDPE | 5 | 289.35 | moderate | local | 60 | 0.12 | 0 | 42 | 6 | 25 | good | 0 | low | residential | 210 | 0 |
| 7 | 100 | Galvanized steel | 17 | 55.97 | moderate | local | 40 | 0.27 | 0 | 9 | 6 | 6 | good | 0 | low | residential | 45 | 0 |
| 3154 | 75 | Galvanized steel | 17 | 22.84 | moderate | local | 46 | 1.47 | 0 | 5 | 6 | 3 | good | 0 | low | residential | 25 | 0 |
| 766 | 50 | Galvanized steel | 43 | 121.75 | moderate | secondary | 36 | 0.21 | 0 | 17 | 6 | 10 | good | 0 | low | residential | 85 | 0 |
| 549 | 50 | Galvanized steel | 43 | 21.82 | moderate | secondary | 44 | 0.37 | 0 | 5 | 6 | 3 | good | 0 | low | residential | 25 | 0 |
| P-1 | 75 | Galvanized steel | 17 | 233.08 | moderate | local |  | 0 | 1 | 32 | 6 | 23 | good | 0 | low | residential | 160 | 0 |

# 4 Results and discussion of application of different MCDM techniques to identify the proper water loss management strategies[4]

This section is structured as follows: First, the outcomes of application of different MCDM techniques to identify the proper water loss management strategies are displayed in association with displaying the outcomes of sensitivity analyses. Second, a discussion of the outcomes that are resulted from the application of different MCDM techniques is carried out.

## 4.1 Results of application of different MCDM techniques to identify the proper water loss management strategies

### 4.1.1 Application of traditional Analytic Hierarchy Process (AHP)

To prioritize the different elements of the hierarchical structure **(Figure 8-Section 2.1.1)** of decision making in water loss management framework with the aim to nominate the most appropriate strategy to reduce water losses simultaneously with considering different concerns of different stakeholders, sustainability dimensions and boundary conditions, three levels of decision matrices were derived. Each entry represents the evaluation of preferences of one element over the other with respect to achieving the goal in the above level. For level 2, as an example, the evaluation is done among the four main criteria with respect to the overall goal in Level 1, and so on for the other levels (i.e. level 3 and level 4).

These matrices comprise all necessary pairwise comparisons at each level. This process, which is a technical activity, has been accomplished by the expert team after a thorough discussion related to the proposed methodology and the hierarchy structure layout. The matrices were derived for each group of experts (DM1 who represents the first group of policy makers; DM2 who represents the second group of policy makers; DM3 who represents the environmental group, and DM4 who represents the operator of water systems) and arranged according to the following form:

- Matrix M1, represents the evaluation of the set of criteria (economic, environmental, technical and socio-economic) with respect to the overall goal. The following matrix shows, as an example, the output of preferences of DM4:

| | **Overall goal** | **Economic (MC1)** | **Environmental (MC2)** | **Technical (MC3)** | **Socio-economic (MC4)** |
|---|---|---|---|---|---|
| **M1** | **Economic (MC1)** | 1 | 9 | 7 | 7 |
| | **Environmental(MC2)** | 1/9 | 1 | 1 | 3 |
| | **Technical (MC3)** | 1/7 | 1 | 1 | 3 |
| | **Socio-economic (MC4)** | 1/7 | 1/3 | 1/3 | 1 |

- Matrices M2.1 to M2.4, represent the evaluation of sub criteria (i.e. evaluation criteria) with respect to their own criterion in the upper level, e.g. the evaluation criteria under the economic criterion that include generation of revenue, capital costs, operation and maintenance costs and benefit period will be evaluated with respect to the economic

[4] Parts of this chapter have been published in (Zyoud *et al.* 2016a; Zyoud *et al.* 2016b; Zyoud & Fuchs-Hanusch 2017a).

criterion in the above level and so on for the others. The resulted matrices of preferences of DM4 at this level are displayed below as an example.

| | Economic MC1 | Revenue generation (EC1-MC1) | Capital costs (EC2-MC1) | O & M costs (EC3-MC1) | Benefit period (EC4-MC1) |
|---|---|---|---|---|---|
| M2.1 | Revenue generation (EC1-MC1) | 1 | 5 | 7 | 9 |
| | Capital costs (EC2-MC1) | 1/5 | 1 | 3 | 9 |
| | O & M costs (EC3-MC1) | 1/7 | 1/3 | 1 | 3 |
| | Benefit period (EC4-MC1) | 1/9 | 1/9 | 1/3 | 1 |

| | Environmental MC2 | Water preservation (EC5-MC2) | Energy saved (EC6-MC2) |
|---|---|---|---|
| M2.2 | Water preservation (EC5-MC2) | 1 | 7 |
| | Energy saved (EC6-MC2) | 1/7 | 1 |

| | Technical MC3 | Supply reliability (EC7-MC3) | Flexibility (EC8-MC3) |
|---|---|---|---|
| M2.3 | Supply reliability (EC7-MC3) | 1 | 7 |
| | Flexibility (EC8-MC3) | 1/7 | 1 |

| | Socio-economic MC4 | Affordability (EC9-MC4) | Water quality (EC10-MC4) |
|---|---|---|---|
| M2.4 | Affordability (EC9-MC4) | 1 | 1/3 |
| | Water quality (EC10-MC4) | 3 | 1 |

- Matrices M3.1 to M3.10, represent the evaluation of performance of alternatives that are located in the last level against the evaluation criteria in the above level. The set of the ten matrices, M3.1 to M3.10, will be generated by performing tradeoffs based on pairwise comparisons among the ten alternatives, Alt. 1 to Alt. 10, with respect to each of the ten evaluation criteria (i.e. M3.1 matrix includes the tradeoffs among the ten alternatives with respect to evaluation criterion of generation of revenue). Each input in these decision matrices represents the relative importance of one alternative over another for a given evaluation criterion. The preferences of DM4 for M3.2 matrix have been illustrated to reflect their preferences among the ten proposed alternatives with respect to capital costs evaluation criterion in the upper level.

| | Capital costs (EC2-MC1) | Active leakage control (Alt. 1) | Passive leakage control (Alt. 2) | Pressure control (Alt. 3) | Establishment of DMAs (Alt. 4) | Asset management (Alt. 5) | Replacement of water meters (Alt. 6) | Improving repairs (Alt. 7) | Control of illegal use (Alt. 8) | Utilizing advanced techniques (Alt. 9) | Public awareness (Alt. 10) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| M3.2 | **Active leakage control (Alt. 1)** | 1 | 3 | 1/5 | 1/3 | 1/7 | 1/5 | 3 | 1/3 | 1/7 | 5 |
| | **Passive leakage control (Alt. 2)** | 1/3 | 1 | 1/7 | 1/7 | 1/9 | 1/7 | 1 | 1/3 | 1/5 | 3 |
| | **Pressure control (Alt. 3)** | 5 | 7 | 1 | 1 | 1/5 | 1 | 5 | 5 | 1/3 | 7 |
| | **Establishment of DMAs (Alt. 4)** | 3 | 7 | 1 | 1 | 1/5 | 1 | 7 | 5 | 1/3 | 7 |
| | **Asset management (Alt. 5)** | 7 | 9 | 5 | 5 | 1 | 3 | 7 | 5 | 3 | 9 |
| | **Replacement of water meters (Alt. 6)** | 5 | 7 | 1 | 1 | 1/3 | 1 | 1 | 3 | 1 | 5 |
| | **Improving repairs (Alt. 7)** | 1/3 | 1 | 1/5 | 1/7 | 1/7 | 1 | 1 | 1/3 | 1/7 | 3 |
| | **Control of illegal use (Alt. 8)** | 3 | 3 | 1/5 | 1/5 | 1/5 | 1/3 | 3 | 1 | 1/5 | 5 |
| | **Utilizing advanced techniques (Alt. 9)** | 7 | 5 | 3 | 3 | 1/3 | 1 | 7 | 5 | 1 | 7 |
| | **Public awareness (Alt. 10)** | 1/5 | 1/3 | 1/7 | 1/7 | 1/9 | 1/5 | 1/3 | 1/5 | 1/7 | 1 |

The consistency results for the decision matrices in the second and third levels of the hierarchy structure were acceptable and within Saaty's suggestions (CR <= 10%). For DM1, CR values were (4.5% -M1, 4.3%-M2.1), for DM2 (7.0%-M1, 4.03%-M2.1), for DM3 (6.8%-M1, 5.5%-M2.1), for DM4 (7.6%-M1, 9.6%-M2.1). For (M2.2, M2.3, and M2.4) matrices in the third level, the results were completely consistent as they consist of two elements only. The CR values for the last level showed figures larger than 10% in some cases. Therefore the consistency was improved until achieving CR values less than 10%. The results of group decision making were based on employing the methods explained in **(Section 2.1.2)**: the GMM and the WAMM methods. The procedure of traditional AHP technique in deriving the priority weights of different hierarchy structure elements is followed. The results of priority weights of criteria, evaluation criteria and alternatives are displayed in details in **Appendix D** for individual DMs (i.e. DM1, DM2, DM3 and DM4) and for group decision making (i.e. GMM and WAMM methods). The global weights of alternatives were derived by aggregating the weights through the hierarchy structure.

The final results of priority vector of weights of main criteria, evaluation criteria and alternatives are shown in Figures 19, 20 and 21, respectively. The preferences of DMs towards the main criteria, Figure 19, were distinct from each other. For DM1, the socio-economic aspects with a percentage of 56% was the most important, followed by economic aspects with 26%. The priorities of DM2 were devoted first to the economic aspects (66%), followed by the environmental aspects (20%). The focus of DM3 was mainly on environmental aspects (48%), followed by socio-economic aspects (33%), while for DM4 the focus was on economic aspects (69%), and followed distantly by nearly same priorities for technical and environmental aspects. The economic aspects were the predominant ones in group decision making with a value around 45% for each of AHP-GMM and AHP-WAMM.

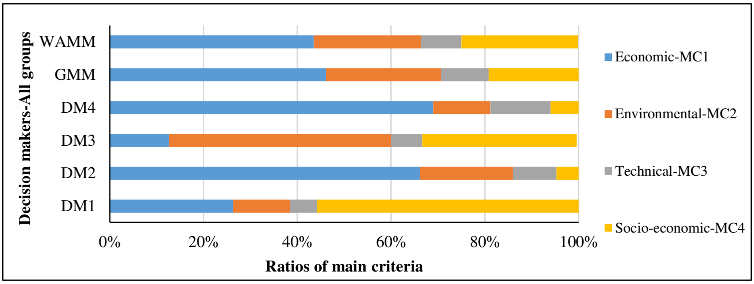



**Figure 19.** Total priority weights of objective class criteria-main criteria (Level 2-Figure 8) for individual groups of decision makers and for group decision making.

The differences in preferences of different DMs are clear at evaluation criteria level as shown in Figure 20. The potential of alternative in increasing the revenue (EC1-MC1) as a result of its application in management of water losses gained the highest priority in group decision making. It is followed by the potential of alternative in preserving water and reducing the wastes (EC5-MC2).

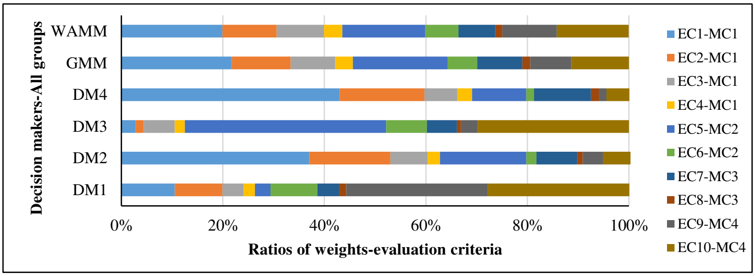



**Figure 20.** Total priority weights of evaluation criteria (Level 3 –Figure 8) for individual groups of decision makers and for group decision making.

The alternatives concerned with pressure management (Alt. 3), establishment of district metered areas (DMAs) (Alt. 4), utilizing advanced techniques (Alt. 9), and asset management (Alt. 5) gained, generally, high priorities compared to other alternatives at individual and group decision making as shown in Figure 21. Otherwise, public awareness and educational campaign alternative (Alt. 10) gained the least priority in general.

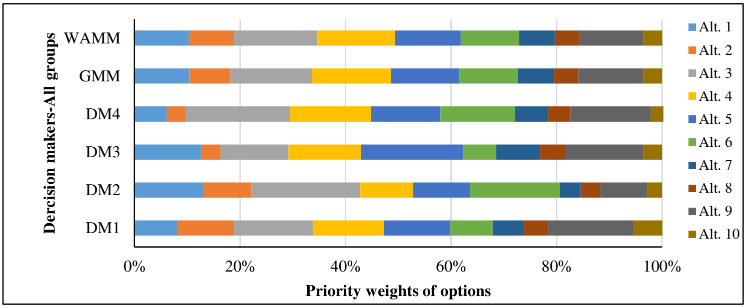



**Figure 21.** Total priority weights of alternatives (Level 4-Figure 8) for individual groups of decision makers and for group decision making.

The results of the dynamic sensitivity analysis and the stability intervals are shown in Table 9 below. For example, the economic criterion with a normalized weight of 46.1% has a stability interval of 25.3% with minimum threshold of 29.6% and maximum threshold of 54.9%. This means that the criterion can be weighted within the previous limits without affecting the ranking of alternatives. Details of the dynamic sensitivity analysis are displayed in **Appendix F.**

**Table 9.** Weight sensitivity analysis of group on strategy ranking

| Main criteria | Min. weight | Value | Max. weight | Stability interval |
|---|---|---|---|---|
| **Economic** | 29.6% | 46.1% | 54.9% | 25.3% |
| **Environmental** | 18.0% | 24.5% | 32.2% | 14.2% |
| **Technical** | 7.1% | 10.2% | 25.5% | 18.4% |
| **Socio-economic** | 7.0% | 19.2% | 69.2% | 62.2% |

## 4.1.2 Application of Fuzzy AHP techniques and comparative analysis between AHP and Fuzzy AHP techniques

The generated matrices in case of employing Fuzzy AHP technique are same, in terms of arrangement, as in case of traditional AHP with entries in the form of TFNs (i.e. it was possible to develop three levels of decision matrices for the three levels under the overall goal-Figure 8). The individual matrices for all groups of DMs with TFNs inputs are aggregated by three different scenarios of aggregation (i.e. WAM1, WAM2 and WAM3) to build the final comparison matrices as explained in details in **(Section 2.1.3.1)** for the application of extent analysis Fuzzy AHP method. For the application of Modified Fuzzy AHP technique, the evaluations of different groups of DMs in the form of TFNs were aggregated by employing the geometric mean over the evaluations of all individual groups as explained in details in **(Section 2.1.3.1).**

The M2.1 matrices for all groups of DMs are displayed below in one matrix. This fuzzy pairwise comparison matrix represents the evaluations of four DMs among the set of evaluation criteria under the economic main criterion in the form of TFNs. The entries represent the tradeoffs among generation of revenue (EC1-MC1), capital costs (EC2-MC1), operation and maintenance costs (EC3-MC1) and benefit period (EC4-MC1) with respect to economic aspects.

| | Economic main criterion (MC1) | | Generation of revenue (EC1-MC1) | Capital costs (EC2-MC1) | O & M costs (EC3-MC1) | Benefit period (EC4-MC1) |
|---|---|---|---|---|---|---|
| M2.1 | Generation of revenue (EC1-MC1) | DM1 Policy makers 1 | (1, 1, 1) | (1, 1, 1) | (1, 3, 5) | (3, 5, 7) |
| | | DM2 Policy makers 2 | (1, 1, 1) | (1, 3, 5) | (5, 7, 9) | (7, 9, 9) |
| | | DM3 Environmental group | (1, 1, 1) | (1, 3, 5) | (1/5, 1/3, 1) | (1, 1, 1) |
| | | DM4 Water utility | (1, 1, 1) | (3, 5, 7) | (5, 7, 9) | (7, 9, 9) |
| | Capital costs (EC2-MC1) | DM1 Policy makers 1 | (1, 1, 1) | (1, 1, 1) | (1, 3, 5) | (1, 3, 5) |
| | | DM2 Policy makers 2 | (1/5, 1/3, 1) | (1, 1, 1) | (1, 3, 5) | (5, 7, 9) |
| | | DM3 Environmental group | (1/5, 1/3, 1) | (1, 1, 1) | (1/5, 1/3, 1) | (1, 1, 1) |
| | | DM4 Water utility | (1/7, 1/5, 1/3) | (1, 1, 1) | (1, 3, 5) | (7, 9, 9) |
| | O & M costs (EC3-MC1) | DM1 Policy makers 1 | (1/5, 1/3, 1) | (1/5, 1/3, 1) | (1, 1, 1) | (1, 3, 5) |
| | | DM2 Policy makers 2 | (1/9, 1/7, 1/5) | (1/5, 1/3, 1) | (1, 1, 1) | (3, 5, 7) |
| | | DM3 Environmental group | (1, 3, 5) | (1, 3, 5) | (1, 1, 1) | (1, 3, 5) |
| | | DM4 Water utility | (1/9, 1/7, 1/5) | (1/5, 1/3, 1) | (1, 1, 1) | (1, 3, 5) |
| | Benefit period (EC4-MC1) | DM1 Policy makers 1 | (1/7, 1/5, 1/3) | (1/5, 1/3, 1) | (1/5, 1/3, 1) | (1, 1, 1) |
| | | DM2 Policy makers 2 | (1/9, 1/9, 1/7) | (1/9, 1/7, 1/5) | (1/7, 1/5, 1/3) | (1, 1, 1) |
| | | DM3 Environmental group | (1, 1, 1) | (1, 1, 1) | (1/5, 1/3, 1) | (1, 1, 1) |
| | | DM4 Water utility | (1/9, 1/9, 1/7) | (1/9, 1/9, 1/7) | (1/5, 1/3, 1) | (1, 1, 1) |

Note 1: all inputs for the diagonal will be (1, 1, 1) as the comparison is held between the evaluation criteria itself.
Note 2: all inputs below the diagonal of the comparison matrix will be reciprocal to the inputs above the diagonal.

The final aggregated pairwise comparison matrix of the above matrices based on the weight aggregation method WAM1 for extent analysis Fuzzy AHP and by geometric mean operator for modified Fuzzy AHP are displayed below, respectively.

| | Economic main criterion (MC1) | Generation of revenue (EC1-MC1) | Capital costs (EC2-MC1) | O & M costs (EC3-MC1) | Benefit period (EC4-MC1) |
|---|---|---|---|---|---|
| M2.1 (Aggregated based on WAM1) | Generation of revenue (EC1-MC1) | (1, 1, 1) | (1, 3, 7) | (0.2, 4.33, 9) | (1, 6, 9) |
| | Capital costs (EC2-MC1) | (0.14, 0.467, 1) | (1, 1, 1) | (0.2, 2.33, 5) | (1, 5, 9) |
| | O & M costs (EC3-MC1) | (0.11, 0.905, 5) | (0.2, 1, 5) | (1, 1, 1) | (1, 3.5, 7) |
| | Benefit period (EC4-MC1) | (0.11, 0.356, 1) | (0.11, 0.397, 1) | (0.14, 0.3, 1) | (1, 1, 1) |

| | Economic main criterion (MC1) | Generation of revenue (EC1-MC1) | Capital costs (EC2-MC1) | O & M costs (EC3-MC1) | Benefit period (EC4-MC1) |
|---|---|---|---|---|---|
| M2.1 (Aggregated based on geometric mean) | Generation of revenue (EC1-MC1) | (1, 1, 1) | (1.32, 2.59, 3.64) | (1.5, 2.64, 4.49) | (3.48, 4.49, 4.88) |
| | Capital costs (EC2-MC1) | (0.27, 0.39, 0.76) | (1, 1, 1) | (0.67, 1.73, 3.34) | (2.43, 3.71, 4.49) |
| | O & M costs (EC3-MC1) | (0.22, 0.38, 0.67) | (0.3, 0.58, 1.5) | (1, 1, 1) | (1.32, 3.41, 5.44) |
| | Benefit period (EC4-MC1) | (0.20, 0.22, 0,28) | (0.22, 0.27, 0.41) | (0.18, 0.29, 0.76) | (1, 1, 1) |

The procedure of deriving the priority weights of different elements of decision making problem as explained in **(Section 2.1.3.1)** was followed for the extent analysis Fuzzy AHP and modified Fuzzy AHP techniques. The results are displayed in details in **Appendix F**. Graphical illustration of results of priority weights of main criteria, evaluation criteria, and alternatives have been demonstrated to compare the outputs by different employed methods in Figures 22, 23, 24 and

25, respectively. As shown in Figure 22, the economic aspects were the predominant during the application of most techniques. The technical main criterion value was distorted to zero in case of employing WAM2-Fuzzy AHP technique.

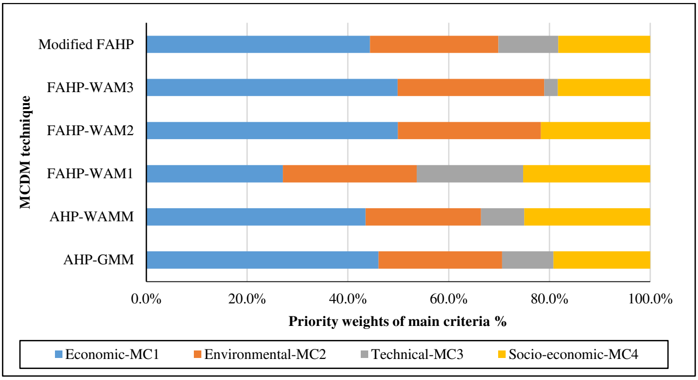



**Figure 22.** Distribution of weights of main criteria.

Figure 23 shows that, the problem of null weights has also been appeared at evaluation criteria level during the application of FAHP-WAM2 and FAHP-WAM3 techniques and for the same set of evaluation criteria (i.e. Benefit period (EC1-MC1), Energy saved (EC6-MC2) and Flexibility of alternative (EC8-MC3)).

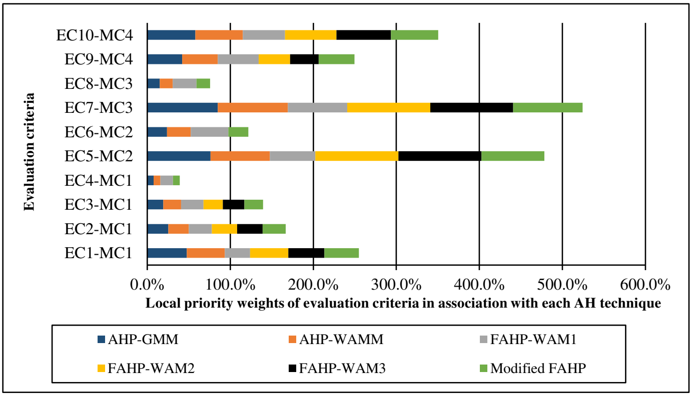



**Figure 23.** Distribution of local priority weights of evaluation criteria.

Figure 24 shows the outcomes of global priority weights of evaluation criteria resulted from the multiplication of local priority weights of each evaluation criterion by the weight of its main criterion in the upper level of the hierarchy structure. In general, the potential of alternative to generate revenue (EC1-MC1) and preserve water in addition to reduction of wastes (EC5-MC2) were with high priority as in case of applying traditional AHP techniques.

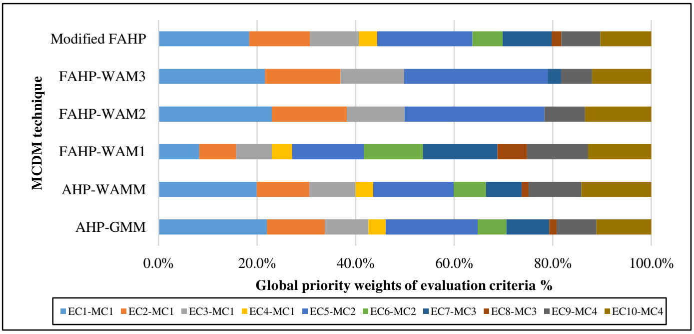



**Figure 24.** Distribution of global priority weights of evaluation criteria by different MCDM techniques.

The ranking of alternatives in group decision making was similar for the two traditional AHP techniques (i.e. AHP-GMM and AHP-WAMM). The modified FAHP ranked the alternatives in a nearly similar way to traditional AHP techniques as shown in Figure 25. The pressure management (Alt. 3) was ranked in the top positions by most of applied techniques. The least preferred alternatives in most cases were controlling of illegal use of water (Alt. 8) and public awareness (Alt. 10).

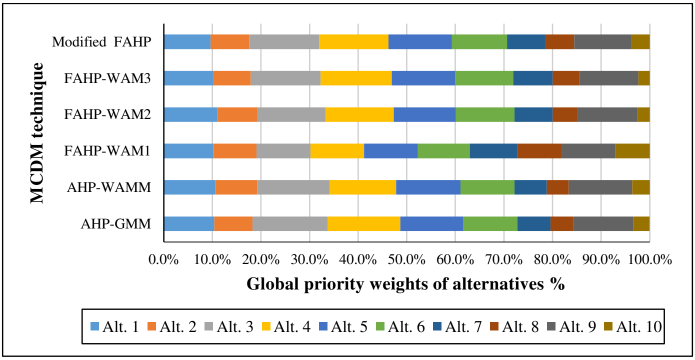



**Figure 25.** Distribution of global priority weights of alternatives by different MCDM techniques.

The lowest values of RMSE were recorded for modified FAHP technique as it is shown in Figure 26 and Figure 27. The total RMSE values were 1.03, 0.73, 0.74, and 0.19 for FAHP-WAM1, FAHP-WAM2, FAHP-WAM3, and modified FAHP, respectively, when the deviations are calculated with respect to the reference outputs of AHP-GMM technique. The RMSE values were 0.91, 0.77, 0.81 and 0.23 for FAHP-WAM1, FAHP-WAM2, FAHP-WAM3, and modified FAHP, respectively, when the deviations are calculated with respect to the reference outputs of AHP-WAMM technique.

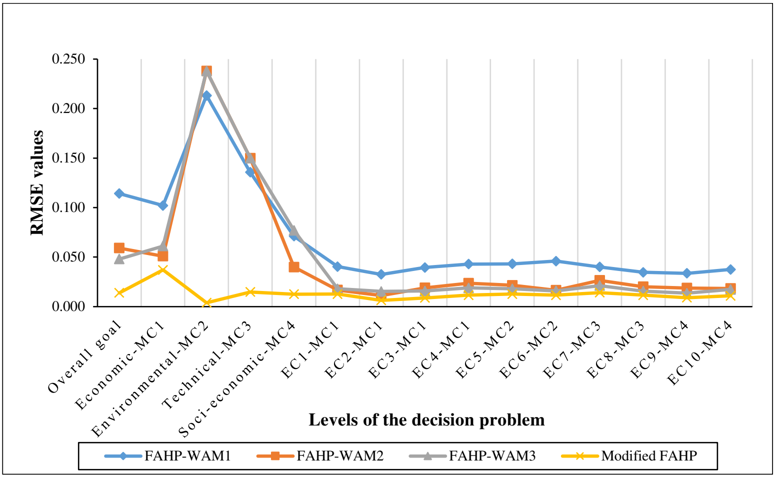



**Figure 26.** RMSE values (Fuzzy AHP methods with respect to traditional AHP method–GMM technique).

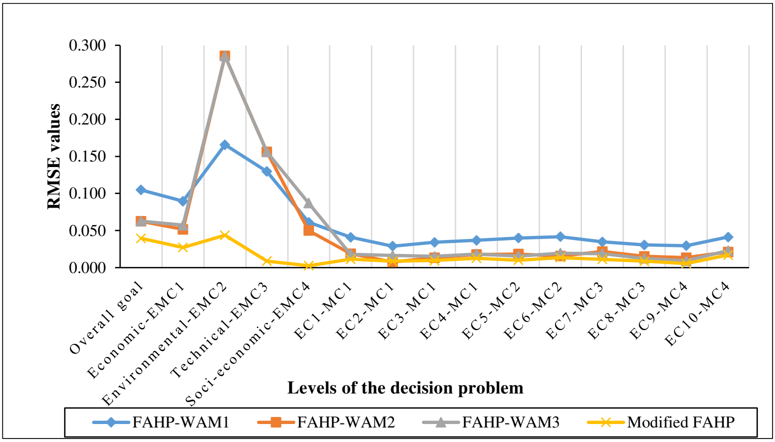


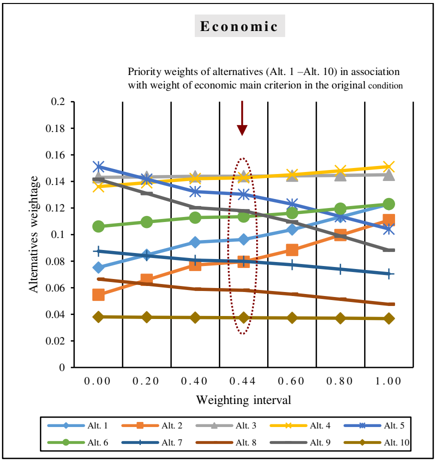

**Figure 27.** RMSE values (Fuzzy AHP methods with respect to traditional AHP method–WAMM technique).

The values of Spearman Correlation Coefficient (*R*) as shown in Table 10 are ranging between 0.8909 and 1. The two traditional AHP techniques are perfectly correlated in terms of ranking alternatives.

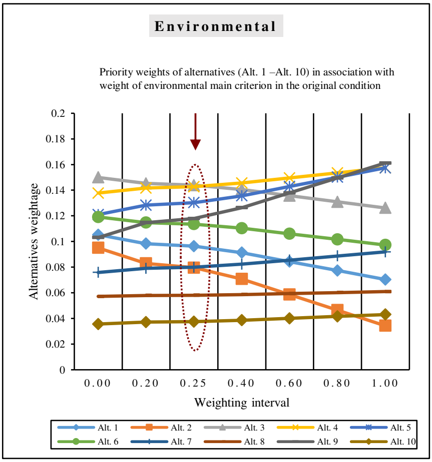
**Table 10.** Values of Spearman Correlation Coefficient (*R*)

| | AHP-GMM | AHP-WAMM | FAHP-WAM1 | FAHP-WAM2 | FAHP-WAM3 | Modified FAHP |
|---|---|---|---|---|---|---|
| AHP-GMM | 1 | 1 | 0.9273 | 0.9879 | 0.9758 | 0.9879 |
| AHP-WAMM | | 1 | 0.9273 | 0.9879 | 0.9758 | 0.9879 |
| FAHP-WAM1 | | | 1 | 0.8909 | 0.9152 | 0.9512 |
| FAHP-WAM2 | | | | 1 | 0.9879 | 0.9758 |
| FAHP-WAM3 | | | | | 1 | 0.9879 |
| Modified FAHP | | | | | | 1 |

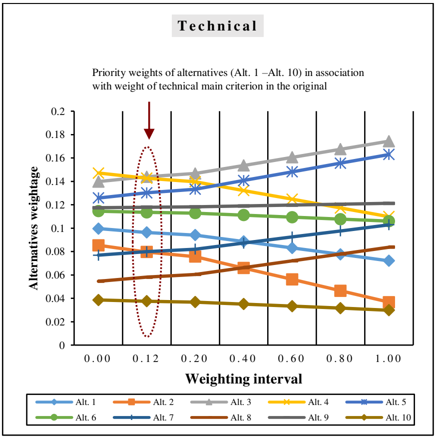
The results of sensitivity analysis has been displayed in association with its application for modified FAHP as shown in Figure 28.A to Figure 28.D. For the other methods, the results of sensitivity analysis are displayed in **Appendix G.**



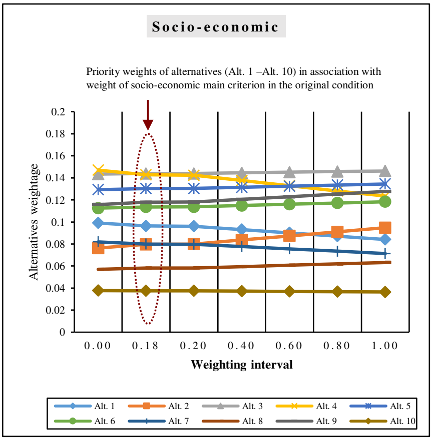

28. A)




28. B)




28. C)




28. D)

**Figure 28.** Sensitivity analysis of the priority weights of alternatives (Alt.1 – Alt. 10) for modified Fuzzy AHP method at each different main criteria's weight interval (0, 1): **28.A** economic, **28.B** environmental, **28.C** technical and **28. D** socio-economic.

### 4.1.3 Application of an integrated methodology of Fuzzy AHP and Fuzzy TOPSIS techniques

Applying the Fuzzy AHP technique implies the construction of two levels of pairwise comparison (PC) matrices for Level 2 and Level 3 under the overall goal in the hierarchy structure (Figure 8). The tradeoff among the elements in each level was performed with respect to the elements in the above level by using the linguistic terms from **Table 3-Section 2.1.3.1** instead of using precise and strict values. For the second level, the tradeoff was done among the main criteria with respect to the overall goal in level 1. For the third level, the tradeoff was done among the elements of evaluation criteria with respect to their own criterion in the second level. Experts from all three groups of DMs have participated to this technical activity. The preferences and tradeoffs of DMs after that have been translated into TFNs with their reciprocals in decision matrices. The aggregation of the preferences to build the group decision making preferences was performed by employing three methods of aggregation (WAM1, WAM2 and WAM3) as explained in details in **Section 2.1.3.1** and Zyoud *et al.* (2016a).

The M2.1 matrices for all groups of DMs are displayed below, as an example, in one matrix. This fuzzy pairwise comparison matrix represents the evaluations of three DMs ($DM1_{\text{Policy makers 1}}$, $DM2_{\text{Policy makers 2}}$ and $DM3_{\text{Water utility}}$) among the set of evaluation criteria under the economic main criterion in the form of Linguistic terms. The entries represent the tradeoffs among generation of revenue (EC1-MC1), capital costs (EC2-MC1), operation and maintenance costs (EC3-MC1) and benefit period (EC4-MC1) with respect to economic aspects.

| | Economic main criterion (MC1) | | Generation of revenue (EC1-MC1) | Capital costs (EC2-MC1) | O & M costs (EC3-MC1) | Benefit period (EC4-MC1) |
|---|---|---|---|---|---|---|
| M2.1 | Generation of revenue (EC1-MC1) | DM1 Policy makers 1 | EI | MI | SI | SI |
| | | DM2 Policy makers 2 | EI | EXI | VSI | SI |
| | | DM3 Water utility | EI | (VSI) | (SI) | MI |
| | Capital costs (EC2-MC1) | DM1 Policy makers 1 | | EI | (SI) | (SI) |
| | | DM2 Policy makers 2 | | EI | (VSI) | (SI) |
| | | DM3 Water utility | | EI | MI | SI |
| | O & M costs (EC3-MC1) | DM1 Policy makers 1 | | | EI | MI |
| | | DM2 Policy makers 2 | | | EI | SI |
| | | DM3 Water utility | | | EI | VSI |
| | Benefit period (EC4-MC1) | DM1 Policy makers 1 | | | | EI |
| | | DM2 Policy makers 2 | | | | EI |
| | | DM3 Water utility | | | | EI |

The entries results in TFNs as follows:

| | Economic main criterion (MC1) | | Generation of revenue (EC1-MC1) | Capital costs (EC2-MC1) | O & M costs (EC3-MC1) | Benefit period (EC4-MC1) |
|---|---|---|---|---|---|---|
| M2.1 | Generation of revenue (EC1-MC1) | DM1 Policy makers 1 | (1,1,1) | (1,3,5) | (3,5,7) | (3,5,7) |
| | | DM2 Policy makers 2 | (1,1,1) | (7,9,9) | (5,7,9) | (3,5,7) |
| | | DM3 Water utility | (1,1,1) | (1/9,1/7,1/5) | (1/7,1/5,1/3) | (1,3,5) |
| | Capital costs (EC2-MC1) | DM1 Policy makers 1 | (1/7,1/5,1/3) | (1,1,1) | (1/7,1/5,1/3) | (1/7,1/5,1/3) |
| | | DM2 Policy makers 2 | (1/9,1/9,1/7) | (1,1,1) | (1/9,1/7,1/5) | (1/7,1/5,1/3) |
| | | DM3 Water utility | (5,7,9) | (1,1,1) | (1,3,5) | (3,5,7) |
| | O & M costs (EC3-MC1) | DM1 Policy makers 1 | (1/7,1/5,1/3) | (3,5,7) | (1,1,1) | (1,3,5) |
| | | DM2 Policy makers 2 | (1/9,1/7,1/5) | (5,7,9) | (1,1,1) | (3,5,7) |
| | | DM3 Water utility | (3,5,7) | (1/5,1/3,1) | (1,1,1) | (5,7,9) |
| | Benefit period (EC4-MC1) | DM1 Policy makers 1 | (1/7,1/5,1/3) | (3,5,7) | (1/5,1/3,1) | (1,1,1) |
| | | DM2 Policy makers 2 | (1/7,1/5,1/3) | (3,5,7) | (1/7,1/5,1/3) | (1,1,1) |
| | | DM3 Water utility | (1/5,1/3,1) | (1/7,1/5,1/3) | (1/9,1/7,1/5) | (1,1,1) |

The final aggregated pairwise comparison matrix of the above matrices based on the weight aggregation method WAM1 for the extent analysis Fuzzy AHP is as follows,

| | Economic main criterion (MC1) | Generation of revenue (EC1-MC1) | Capital costs (EC2-MC1) | O & M costs (EC3-MC1) | Benefit period (EC4-MC1) |
|---|---|---|---|---|---|
| **M2.1 (Aggregated based on WAM1)** | **Generation of revenue (EC1-MC1)** | (1,1,1) | (0.11,4.05,9) | (0.14,4.07,9) | (1,4.33,7) |
| | **Capital costs (EC2-MC1)** | (0.11,2.48,9) | (1,1,1) | (0.11,1.11,5) | (0.14,1.8,7) |
| | **O & M costs (EC3-MC1)** | (0.11,1.78,7) | (0.2,4.11,9) | (1,1,1) | (1,5,9) |
| | **Benefit period (EC4-MC1)** | (0.14,3.40,7) | (3,5,7) | (0.11,0.23,1) | (1,1,1) |

The extent analysis Fuzzy AHP technique has been followed to derive the priority vector of weights for main and evaluation criteria. The graphical illustration of these results are displayed in Figures 29, 30 and 31, respectively. More details about the detailed steps in deriving the priority vector of weights of main and evaluation criteria can be found in Zyoud *et al.* (2016a). Figure 29 shows that the economic, technical and also the socio economic main criteria are preferred by DMs compared to the environmental aspects.

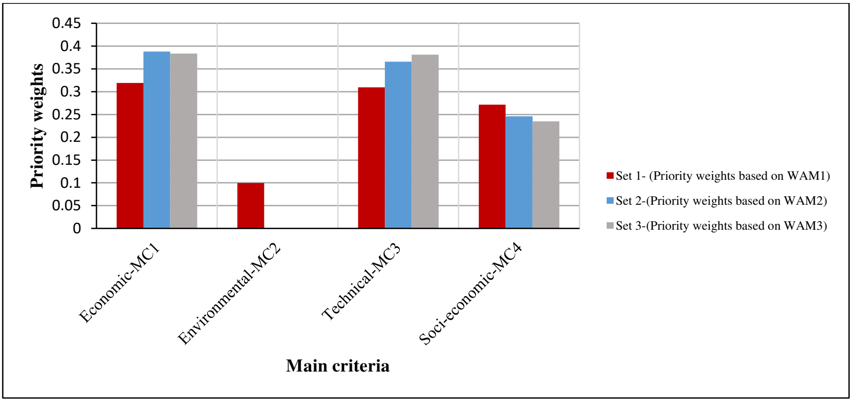



**Figure 29.** Priority weights of main criteria (Three sets) generated by Fuzzy AHP technique based on using three different weighted aggregation methods of DMs' evaluations (WAM1, WAM2 and WAM3).

Figure 30 shows that, the evaluation criterion that is related to flexibility of alternative (EC8-MC3) attracted the highest priority by most of applied aggregation techniques. It is followed by the affordability of alternative (EC9-MC4) and the potential of alternative in saving energy (EC6-MC2). The global weights of evaluation criteria, illustrated in Figure 31, show that the flexibility evaluation criterion (EC8-MC3) maintained its position in the front for all aggregation techniques.

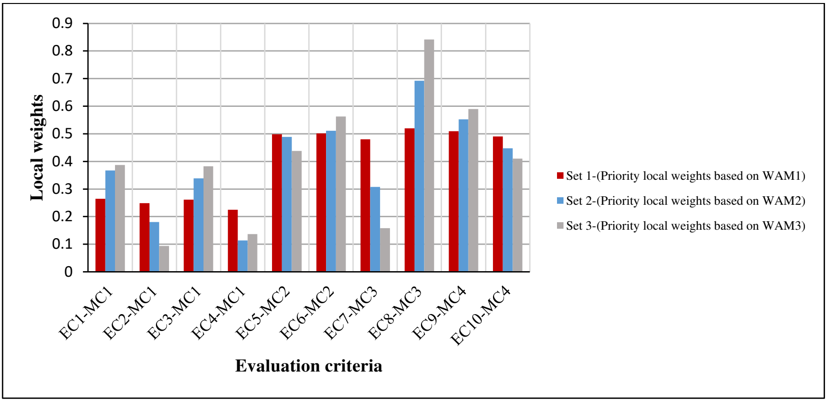



**Figure 30.** Local weights of evaluation criteria (Three sets) generated by Fuzzy AHP technique based on using three different weighted aggregation methods of DMs' evaluations (WAM1, WAM2 and WAM3).

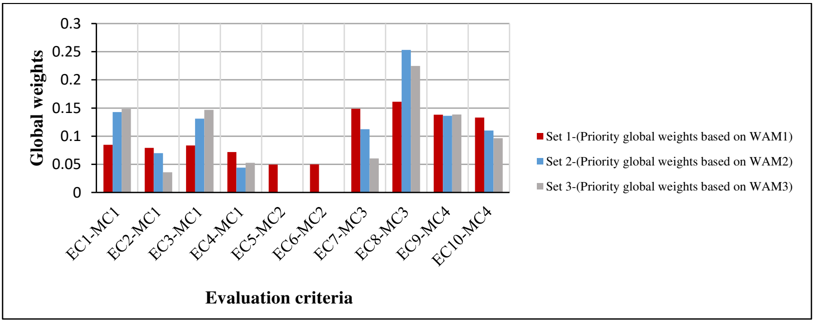



**Figure 31.** Global weights of evaluation criteria (Three sets) generated by Fuzzy AHP technique based on using three different weighted aggregation methods of DMs' evaluations (WAM1, WAM2 and WAM3).

The application of Fuzzy TOPSIS technique required the assigning of the performance of alternatives with respect to the evaluation criteria by using the linguistic terms shown in Table 5 – **Section 2.1.4.1**, converting the linguistic terms into TFNs, aggregation, normalization, weighting of fuzzy ratings of alternatives, and the calculations of separation distances, and $CC_s$ values which represent the importance of alternatives. Table 11 displays the inputs of DMs which represent the evaluation of performance of alternatives towards the evaluation criteria using linguistic terms and their matches in TFNs.

**Table 11.** Rating the performance of alternatives towards the evaluation criteria using linguistic terms by DMs and their matches in TFNs

**Linguistic ratings of the alternatives**

| Evaluation criteria | | EC1-MC1 | EC2-MC1 | EC3-MC1 | EC4-MC1 | EC5-MC2 | EC6-MC2 | EC7-MC3 | EC8-MC3 | EC9-MC4 | EC10-MC4 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Alternatives** | **Decision Makers (DMs)** | | | | | | | | | | |
| | DM1 Policy makers 1 | P | G | F | F | G | P | G | F | P | F |
| **Alt. 1** | DM2 Policy makers 2 | G | F | F | P | VG | G | G | P | F | P |
| | DM3 Water utility | F | P | G | F | G | P | F | F | F | F |
| | DM1 Policy makers 1 | P | P | F | P | G | P | G | F | P | F |
| **Alt. 2** | DM2 Policy makers 2 | F | P | F | P | G | F | G | F | P | P |
| | DM3 Water utility | G | F | G | F | VG | F | G | F | F | G |
| | DM1 Policy makers 1 | F | G | G | F | G | G | F | F | G | F |
| **Alt. 3** | DM2 Policy makers 2 | G | F | G | F | F | F | F | G | F | G |
| | DM3 Water utility | F | F | G | G | G | G | G | F | F | F |
| | DM1 Policy makers 1 | F | F | F | G | F | G | F | G | F | F |
| **Alt. 4** | DM2 Policy makers 2 | P | F | G | P | F | F | P | G | G | G |
| | DM3 Water utility | F | F | G | G | P | F | F | F | F | VG |
| | DM1 Policy makers 1 | F | F | G | P | VG | F | G | P | P | F |
| **Alt. 5** | DM2 Policy makers 2 | F | P | G | P | VG | F | G | P | P | G |
| | DM3 Water utility | P | VP | P | VG | VG | G | G | G | F | G |
| | DM1 Policy makers 1 | G | F | G | F | VG | F | VG | F | P | P |
| **Alt. 6** | DM2 Policy makers 2 | G | F | G | F | VG | VG | VG | P | P | P |
| | DM3 Water utility | VG | P | VG | VG | G | F | F | F | G | F |
| | DM1 Policy makers 1 | P | G | G | F | G | P | G | P | P | VP |
| **Alt. 7** | DM2 Policy makers 2 | P | G | G | P | P | P | F | VP | VP | VP |
| | DM3 Water utility | G | F | VG | VG | VG | F | G | G | F | G |
| | DM1 Policy makers 1 | VG | P | VP | F | G | P | G | P | F | VP |
| **Alt. 8** | DM2 Policy makers 2 | G | F | VP | F | G | G | G | VP | F | VP |
| | DM3 Water utility | VG | G | F | G | VG | G | G | G | VG | F |
| | DM1 Policy makers 1 | F | F | G | F | G | G | G | F | F | P |
| **Alt. 9** | DM2 Policy makers 2 | F | P | F | P | G | G | G | F | G | VP |
| | DM3 Water utility | G | P | G | G | G | VG | VG | G | F | G |
| | DM1 Policy makers 1 | P | P | VP | P | F | P | F | P | P | F |
| **Alt. 10** | DM2 Policy makers 2 | VP | P | P | P | F | P | F | VP | P | G |
| | DM3 Water utility | G | F | F | F | G | F | VG | G | F | G |

**Converting linguistic ratings of the alternatives into TFNs**

| Alternatives | Decision Makers (DMs) | EC1-MC1 | EC2-MC1 | EC3-MC1 | EC4-MC1 | EC5-MC2 | EC6-MC2 | EC7-MC3 | EC8-MC3 | EC9-MC4 | EC10-MC4 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | DM1 | (1,3,5) | (5,7,9) | (3,5,7) | (3,5,7) | (5,7,9) | (1,3,5) | (5,7,9) | (3,5,7) | (1,3,5) | (3,5,7) |
| Alt. 1 | DM2 | (5,7,9) | (3,5,7) | (3,5,7) | (1,3,5) | (7,9,9) | (5,7,9) | (5,7,9) | (1,3,5) | (3,5,7) | (1,3,5) |
| | DM3 | (3,5,7) | (1,3,5) | (5,7,9) | (3,5,7) | (5,7,9) | (1,3,5) | (3,5,7) | (3,5,7) | (3,5,7) | (3,5,7) |
| | DM1 | (1,3,5) | (1,3,5) | (3,5,7) | (1,3,5) | (5,7,9) | (1,3,5) | (5,7,9) | (3,5,7) | (1,3,5) | (3,5,7) |
| Alt. 2 | DM2 | (3,5,7) | (1,3,5) | (3,5,7) | (1,3,5) | (5,7,9) | (3,5,7) | (5,7,9) | (3,5,7) | (1,3,5) | (1,3,5) |
| | DM3 | (5,7,9) | (3,5,7) | (5,7,9) | (3,5,7) | (7,9,9) | (3,5,7) | (5,7,9) | (3,5,7) | (3,5,7) | (5,7,9) |
| | DM1 | (3,5,7) | (5,7,9) | (5,7,9) | (3,5,7) | (5,7,9) | (5,7,9) | (3,5,7) | (3,5,7) | (5,7,9) | (3,5,7) |
| Alt. 3 | DM2 | (5,7,9) | (3,5,7) | (5,7,9) | (3,5,7) | (3,5,7) | (3,5,7) | (3,5,7) | (5,7,9) | (3,5,7) | (5,7,9) |
| | DM3 | (3,5,7) | (3,5,7) | (5,7,9) | (5,7,9) | (5,7,9) | (5,7,9) | (5,7,9) | (3,5,7) | (3,5,7) | (3,5,7) |
| | DM1 | (3,5,7) | (3,5,7) | (3,5,7) | (5,7,9) | (3,5,7) | (5,7,9) | (3,5,7) | (5,7,9) | (3,5,7) | (3,5,7) |
| Alt. 4 | DM2 | (1,3,5) | (3,5,7) | (5,7,9) | (1,3,5) | (3,5,7) | (3,5,7) | (1,3,5) | (5,7,9) | (5,7,9) | (5,7,9) |
| | DM3 | (3,5,7) | (3,5,7) | (5,7,9) | (5,7,9) | (1,3,5) | (3,5,7) | (3,5,7) | (3,5,7) | (3,5,7) | (7,9,9) |
| | DM1 | (3,5,7) | (3,5,7) | (5,7,9) | (1,3,5) | (7,9,9) | (3,5,7) | (5,7,9) | (1,3,5) | (1,3,5) | (3,5,7) |
| Alt. 5 | DM2 | (3,5,7) | (1,3,5) | (5,7,9) | (1,3,5) | (7,9,9) | (3,5,7) | (5,7,9) | (1,3,5) | (1,3,5) | (5,7,9) |
| | DM3 | (1,3,5) | (1,1,1) | (1,3,5) | (7,9,9) | (7,9,9) | (5,7,9) | (5,7,9) | (5,7,9) | (3,5,7) | (5,7,9) |
| | DM1 | (5,7,9) | (3,5,7) | (5,7,9) | (3,5,7) | (7,9,9) | (3,5,7) | (7,9,9) | (3,5,7) | (1,3,5) | (1,3,5) |
| Alt. 6 | DM2 | (5,7,9) | (3,5,7) | (5,7,9) | (3,5,7) | (7,9,9) | (7,9,9) | (7,9,9) | (1,3,5) | (1,3,5) | (1,3,5) |
| | DM3 | (7,9,9) | (1,3,5) | (7,9,9) | (7,9,9) | (5,7,9) | (3,5,7) | (3,5,7) | (3,5,7) | (5,7,9) | (3,5,7) |
| | DM1 | (1,3,5) | (5,7,9) | (5,7,9) | (3,5,7) | (5,7,9) | (1,3,5) | (5,7,9) | (1,3,5) | (1,3,5) | (1,1,1) |
| Alt. 7 | DM2 | (1,3,5) | (5,7,9) | (5,7,9) | (1,3,5) | (1,3,5) | (1,3,5) | (3,5,7) | (1,1,1) | (1,1,1) | (1,1,1) |
| | DM3 | (5,7,9) | (3,5,7) | (7,9,9) | (7,9,9) | (7,9,9) | (3,5,7) | (5,7,9) | (5,7,9) | (3,5,7) | (5,7,9) |
| | DM1 | (7,9,9) | (1,3,5) | (1,1,1) | (3,5,7) | (5,7,9) | (1,3,5) | (5,7,9) | (1,3,5) | (3,5,7) | (1,1,1) |
| Alt. 8 | DM2 | (5,7,9) | (3,5,7) | (1,1,1) | (3,5,7) | (5,7,9) | (5,7,9) | (5,7,9) | (1,1,1) | (3,5,7) | (1,1,1) |
| | DM3 | (7,9,9) | (5,7,9) | (3,5,7) | (5,7,9) | (7,9,9) | (5,7,9) | (5,7,9) | (5,7,9) | (7,9,9) | (3,5,7) |
| | DM1 | (3,5,7) | (3,5,7) | (5,7,9) | (3,5,7) | (5,7,9) | (5,7,9) | (5,7,9) | (3,5,7) | (3,5,7) | (1,3,5) |
| Alt. 9 | DM2 | (3,5,7) | (1,3,5) | (3,5,7) | (1,3,5) | (5,7,9) | (5,7,9) | (5,7,9) | (3,5,7) | (5,7,9) | (1,1,1) |
| | DM3 | (5,7,9) | (1,3,5) | (5,7,9) | (5,7,9) | (5,7,9) | (7,9,9) | (7,9,9) | (5,7,9) | (3,5,7) | (5,7,9) |
| | DM1 | (1,3,5) | (1,3,5) | (1,1,1) | (1,3,5) | (3,5,7) | (1,3,5) | (3,5,7) | (1,3,5) | (1,3,5) | (3,5,7) |
| Alt. 10 | DM2 | (7,9,9) | (1,3,5) | (1,3,5) | (1,3,5) | (3,5,7) | (1,3,5) | (3,5,7) | (1,1,1) | (1,3,5) | (5,7,9) |
| | DM3 | (5,7,9) | (3,5,7) | (3,5,7) | (3,5,7) | (5,7,9) | (3,5,7) | (7,9,9) | (5,7,9) | (3,5,7) | (5,7,9) |

Figure 32 displays the outcomes of the integrated Fuzzy AHP-Fuzzy TOPSIS technique in terms of ranking the alternatives according to the associated values of Closeness Coefficients values (CCs). The pressure management alternative (Alt. 3) was with the highest priority and gained the highest rate of performance by integrating the three weighted aggregation techniques in Fuzzy AHP (WAM1, WAM2 and WAM3), each in turn with Fuzzy TOPSIS technique.

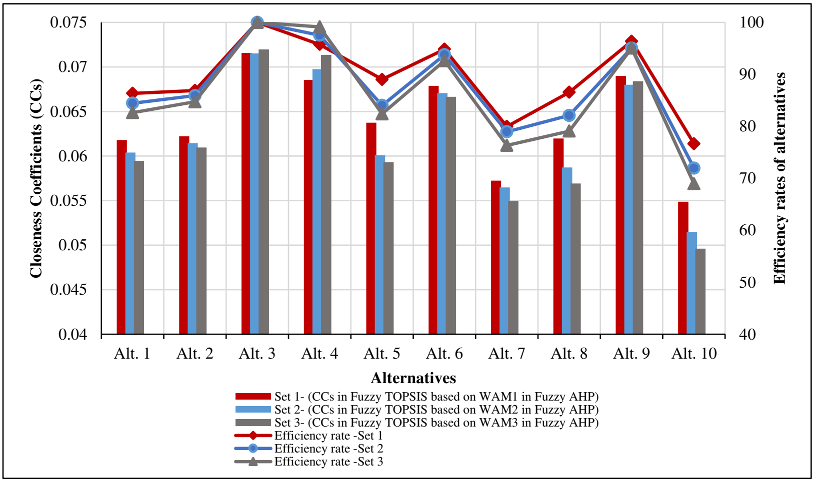



**Figure 32.** Closeness Coefficients values (CCs) for each alternative (Three sets) which represent the ranking of alternatives (by using the outputs of three different weighting aggregation methods in Fuzzy AHP (WAM1; WAM2 and WAM3) as inputs to calculate CCs values for alternatives in Fuzzy TOPSIS method).

Table 12 shows the outputs of CCs values in association with the application of a sensitivity analysis over the WAM1-Fuzzy AHP method. The sensitivity analysis results are illustrated graphically for all aggregation methods (WAM1, WAM2 and WAM3) that are integrated with Fuzzy TOPSIS technique in Figure 33, Figure 34 and Figure 35, respectively.

**Table 12.** Sensitivity Analysis outputs (Changes in CCs values produced by Fuzzy TOPSIS and associated with mutually exchange of weights of evaluation criteria produced by Fuzzy AHP based on the first aggregation method –WAM1)

| Conditions | Mutual exchange of weights of evaluation criteria | | | | | | | | | | CCs- Values | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EC1-MC1 | EC2-MC1 | EC3-MC1 | EC4-MC1 | EC5-MC2 | EC6-MC2 | EC7-MC3 | EC8-MC3 | EC9-MC4 | EC10-MC4 | Alt. 1 | Alt. 2 | Alt. 3 | Alt. 4 | Alt. 5 | Alt. 6 | Alt. 7 | Alt. 8 | Alt. 9 | Alt. 10 |
| **Main** | 0.085 | 0.079 | 0.084 | 0.072 | 0.050 | 0.050 | 0.149 | 0.161 | 0.138 | 0.133 | 0.062 | 0.062 | 0.072 | 0.069 | 0.064 | 0.068 | 0.057 | 0.062 | 0.069 | 0.055 |
| **1** | 0.079 | 0.085 | 0.084 | 0.072 | 0.050 | 0.050 | 0.149 | 0.161 | 0.138 | 0.133 | 0.062 | 0.062 | 0.072 | 0.069 | 0.064 | 0.068 | 0.057 | 0.062 | 0.069 | 0.055 |
| **2** | 0.084 | 0.079 | 0.085 | 0.072 | 0.050 | 0.050 | 0.149 | 0.161 | 0.138 | 0.133 | 0.062 | 0.062 | 0.072 | 0.069 | 0.064 | 0.068 | 0.057 | 0.062 | 0.069 | 0.055 |
| **3** | 0.072 | 0.079 | 0.084 | 0.085 | 0.050 | 0.050 | 0.149 | 0.161 | 0.138 | 0.133 | 0.062 | 0.062 | 0.072 | 0.069 | 0.064 | 0.068 | 0.058 | 0.062 | 0.069 | 0.055 |
| **4** | 0.050 | 0.079 | 0.084 | 0.072 | 0.085 | 0.050 | 0.149 | 0.161 | 0.138 | 0.133 | 0.063 | 0.063 | 0.072 | 0.069 | 0.065 | 0.068 | 0.058 | 0.062 | 0.069 | 0.056 |
| **5** | 0.050 | 0.079 | 0.084 | 0.072 | 0.050 | 0.085 | 0.149 | 0.161 | 0.138 | 0.133 | 0.062 | 0.062 | 0.072 | 0.069 | 0.064 | 0.067 | 0.057 | 0.061 | 0.070 | 0.055 |
| **6** | 0.149 | 0.079 | 0.084 | 0.072 | 0.050 | 0.050 | 0.085 | 0.161 | 0.138 | 0.133 | 0.061 | 0.061 | 0.072 | 0.069 | 0.062 | 0.068 | 0.056 | 0.063 | 0.068 | 0.053 |
| **7** | 0.161 | 0.079 | 0.084 | 0.072 | 0.050 | 0.050 | 0.149 | 0.085 | 0.138 | 0.133 | 0.062 | 0.062 | 0.071 | 0.066 | 0.063 | 0.070 | 0.058 | 0.065 | 0.069 | 0.055 |
| **8** | 0.138 | 0.079 | 0.084 | 0.072 | 0.050 | 0.050 | 0.149 | 0.161 | 0.085 | 0.133 | 0.062 | 0.063 | 0.071 | 0.067 | 0.064 | 0.069 | 0.058 | 0.062 | 0.068 | 0.054 |
| **9** | 0.133 | 0.079 | 0.084 | 0.072 | 0.050 | 0.050 | 0.149 | 0.161 | 0.138 | 0.085 | 0.062 | 0.062 | 0.071 | 0.067 | 0.062 | 0.070 | 0.058 | 0.065 | 0.070 | 0.053 |
| **10** | 0.085 | 0.084 | 0.079 | 0.072 | 0.050 | 0.050 | 0.149 | 0.161 | 0.138 | 0.133 | 0.062 | 0.062 | 0.072 | 0.069 | 0.064 | 0.068 | 0.057 | 0.062 | 0.069 | 0.055 |
| **11** | 0.085 | 0.072 | 0.084 | 0.079 | 0.050 | 0.050 | 0.149 | 0.161 | 0.138 | 0.133 | 0.062 | 0.062 | 0.072 | 0.069 | 0.064 | 0.068 | 0.057 | 0.062 | 0.069 | 0.055 |
| **12** | 0.085 | 0.050 | 0.084 | 0.072 | 0.079 | 0.050 | 0.149 | 0.161 | 0.138 | 0.133 | 0.062 | 0.063 | 0.072 | 0.068 | 0.065 | 0.069 | 0.057 | 0.063 | 0.070 | 0.055 |
| **13** | 0.085 | 0.050 | 0.084 | 0.072 | 0.050 | 0.079 | 0.149 | 0.161 | 0.138 | 0.133 | 0.061 | 0.062 | 0.072 | 0.069 | 0.065 | 0.068 | 0.056 | 0.062 | 0.070 | 0.055 |
| **14** | 0.085 | 0.149 | 0.084 | 0.072 | 0.050 | 0.050 | 0.079 | 0.161 | 0.138 | 0.133 | 0.061 | 0.060 | 0.072 | 0.069 | 0.061 | 0.066 | 0.058 | 0.061 | 0.066 | 0.053 |
| **15** | 0.085 | 0.161 | 0.084 | 0.072 | 0.050 | 0.050 | 0.149 | 0.079 | 0.138 | 0.133 | 0.062 | 0.061 | 0.072 | 0.067 | 0.062 | 0.068 | 0.060 | 0.063 | 0.067 | 0.055 |
| **16** | 0.085 | 0.138 | 0.084 | 0.072 | 0.050 | 0.050 | 0.149 | 0.161 | 0.079 | 0.133 | 0.062 | 0.062 | 0.071 | 0.068 | 0.063 | 0.068 | 0.059 | 0.061 | 0.067 | 0.055 |
| **17** | 0.085 | 0.133 | 0.084 | 0.072 | 0.050 | 0.050 | 0.149 | 0.161 | 0.138 | 0.079 | 0.062 | 0.061 | 0.072 | 0.067 | 0.062 | 0.068 | 0.059 | 0.064 | 0.069 | 0.053 |
| **18** | 0.085 | 0.079 | 0.072 | 0.084 | 0.050 | 0.050 | 0.149 | 0.161 | 0.138 | 0.133 | 0.062 | 0.062 | 0.072 | 0.069 | 0.064 | 0.068 | 0.057 | 0.063 | 0.069 | 0.055 |
| **19** | 0.085 | 0.079 | 0.050 | 0.072 | 0.084 | 0.050 | 0.149 | 0.161 | 0.138 | 0.133 | 0.062 | 0.063 | 0.071 | 0.068 | 0.065 | 0.068 | 0.057 | 0.064 | 0.069 | 0.056 |
| **20** | 0.085 | 0.079 | 0.050 | 0.072 | 0.050 | 0.084 | 0.149 | 0.161 | 0.138 | 0.133 | 0.061 | 0.062 | 0.071 | 0.068 | 0.064 | 0.067 | 0.056 | 0.063 | 0.069 | 0.055 |
| **21** | 0.085 | 0.079 | 0.149 | 0.072 | 0.050 | 0.050 | 0.084 | 0.161 | 0.138 | 0.133 | 0.061 | 0.061 | 0.073 | 0.070 | 0.063 | 0.068 | 0.058 | 0.059 | 0.068 | 0.053 |
| **22** | 0.085 | 0.079 | 0.161 | 0.072 | 0.050 | 0.050 | 0.149 | 0.084 | 0.138 | 0.133 | 0.063 | 0.062 | 0.072 | 0.068 | 0.065 | 0.070 | 0.060 | 0.060 | 0.069 | 0.054 |
| **23** | 0.085 | 0.079 | 0.138 | 0.072 | 0.050 | 0.050 | 0.149 | 0.161 | 0.084 | 0.133 | 0.062 | 0.063 | 0.072 | 0.068 | 0.064 | 0.069 | 0.060 | 0.059 | 0.069 | 0.054 |
| **24** | 0.085 | 0.079 | 0.133 | 0.072 | 0.050 | 0.050 | 0.149 | 0.161 | 0.138 | 0.084 | 0.062 | 0.062 | 0.072 | 0.068 | 0.063 | 0.070 | 0.060 | 0.062 | 0.070 | 0.053 |
| **25** | 0.085 | 0.079 | 0.084 | 0.050 | 0.072 | 0.050 | 0.149 | 0.161 | 0.138 | 0.133 | 0.062 | 0.063 | 0.071 | 0.068 | 0.064 | 0.068 | 0.057 | 0.062 | 0.069 | 0.055 |
| **26** | 0.085 | 0.079 | 0.084 | 0.050 | 0.050 | 0.072 | 0.149 | 0.161 | 0.138 | 0.133 | 0.062 | 0.062 | 0.071 | 0.068 | 0.064 | 0.068 | 0.057 | 0.062 | 0.069 | 0.055 |
| **27** | 0.085 | 0.079 | 0.084 | 0.149 | 0.050 | 0.050 | 0.072 | 0.161 | 0.138 | 0.133 | 0.061 | 0.060 | 0.072 | 0.070 | 0.063 | 0.068 | 0.057 | 0.062 | 0.068 | 0.054 |
| **28** | 0.085 | 0.079 | 0.084 | 0.161 | 0.050 | 0.050 | 0.149 | 0.072 | 0.138 | 0.133 | 0.062 | 0.061 | 0.072 | 0.068 | 0.065 | 0.070 | 0.060 | 0.065 | 0.069 | 0.055 |
| **29** | 0.085 | 0.079 | 0.084 | 0.138 | 0.050 | 0.050 | 0.149 | 0.161 | 0.072 | 0.133 | 0.062 | 0.062 | 0.072 | 0.069 | 0.065 | 0.069 | 0.059 | 0.062 | 0.068 | 0.055 |
| **30** | 0.085 | 0.079 | 0.084 | 0.133 | 0.050 | 0.050 | 0.149 | 0.161 | 0.138 | 0.072 | 0.062 | 0.062 | 0.072 | 0.068 | 0.063 | 0.070 | 0.059 | 0.065 | 0.070 | 0.053 |
| **31** | 0.085 | 0.079 | 0.084 | 0.072 | 0.050 | 0.050 | 0.149 | 0.161 | 0.138 | 0.133 | 0.062 | 0.062 | 0.072 | 0.069 | 0.064 | 0.068 | 0.057 | 0.062 | 0.069 | 0.055 |
| **32** | 0.085 | 0.079 | 0.084 | 0.072 | 0.149 | 0.050 | 0.050 | 0.161 | 0.138 | 0.133 | 0.063 | 0.063 | 0.072 | 0.069 | 0.065 | 0.069 | 0.057 | 0.062 | 0.069 | 0.054 |
| **33** | 0.085 | 0.079 | 0.084 | 0.072 | 0.161 | 0.050 | 0.149 | 0.050 | 0.138 | 0.133 | 0.065 | 0.065 | 0.072 | 0.066 | 0.068 | 0.072 | 0.060 | 0.066 | 0.070 | 0.057 |
| **34** | 0.085 | 0.079 | 0.084 | 0.072 | 0.138 | 0.050 | 0.149 | 0.161 | 0.050 | 0.133 | 0.064 | 0.065 | 0.071 | 0.066 | 0.067 | 0.070 | 0.060 | 0.062 | 0.069 | 0.056 |
| **35** | 0.085 | 0.079 | 0.084 | 0.072 | 0.133 | 0.050 | 0.149 | 0.161 | 0.138 | 0.050 | 0.064 | 0.064 | 0.072 | 0.066 | 0.065 | 0.071 | 0.060 | 0.067 | 0.072 | 0.054 |
| **36** | 0.085 | 0.079 | 0.084 | 0.072 | 0.050 | 0.149 | 0.050 | 0.161 | 0.138 | 0.133 | 0.060 | 0.059 | 0.072 | 0.070 | 0.062 | 0.067 | 0.054 | 0.061 | 0.069 | 0.052 |
| **37** | 0.085 | 0.079 | 0.084 | 0.072 | 0.050 | 0.161 | 0.149 | 0.050 | 0.138 | 0.133 | 0.061 | 0.061 | 0.072 | 0.067 | 0.065 | 0.069 | 0.057 | 0.064 | 0.070 | 0.055 |
| **38** | 0.085 | 0.079 | 0.084 | 0.072 | 0.050 | 0.138 | 0.149 | 0.161 | 0.050 | 0.133 | 0.061 | 0.062 | 0.071 | 0.068 | 0.065 | 0.069 | 0.057 | 0.061 | 0.070 | 0.054 |
| **39** | 0.085 | 0.079 | 0.084 | 0.072 | 0.050 | 0.133 | 0.149 | 0.161 | 0.138 | 0.050 | 0.061 | 0.061 | 0.072 | 0.067 | 0.063 | 0.070 | 0.058 | 0.065 | 0.072 | 0.052 |
| **40** | 0.085 | 0.079 | 0.084 | 0.072 | 0.050 | 0.050 | 0.161 | 0.149 | 0.138 | 0.133 | 0.062 | 0.062 | 0.072 | 0.068 | 0.064 | 0.068 | 0.058 | 0.062 | 0.069 | 0.055 |
| **41** | 0.085 | 0.079 | 0.084 | 0.072 | 0.050 | 0.050 | 0.138 | 0.161 | 0.149 | 0.133 | 0.062 | 0.062 | 0.072 | 0.069 | 0.063 | 0.068 | 0.057 | 0.062 | 0.069 | 0.055 |
| **42** | 0.085 | 0.079 | 0.084 | 0.072 | 0.050 | 0.050 | 0.133 | 0.161 | 0.138 | 0.149 | 0.062 | 0.062 | 0.072 | 0.069 | 0.064 | 0.067 | 0.057 | 0.061 | 0.068 | 0.055 |
| **43** | 0.085 | 0.079 | 0.084 | 0.072 | 0.050 | 0.050 | 0.149 | 0.138 | 0.161 | 0.133 | 0.062 | 0.062 | 0.072 | 0.069 | 0.064 | 0.068 | 0.057 | 0.063 | 0.069 | 0.055 |
| **44** | 0.085 | 0.079 | 0.084 | 0.072 | 0.050 | 0.050 | 0.149 | 0.133 | 0.138 | 0.161 | 0.062 | 0.062 | 0.072 | 0.069 | 0.064 | 0.068 | 0.057 | 0.061 | 0.068 | 0.056 |
| **45** | 0.085 | 0.079 | 0.084 | 0.072 | 0.050 | 0.050 | 0.149 | 0.161 | 0.133 | 0.138 | 0.062 | 0.062 | 0.072 | 0.069 | 0.064 | 0.068 | 0.057 | 0.062 | 0.069 | 0.055 |

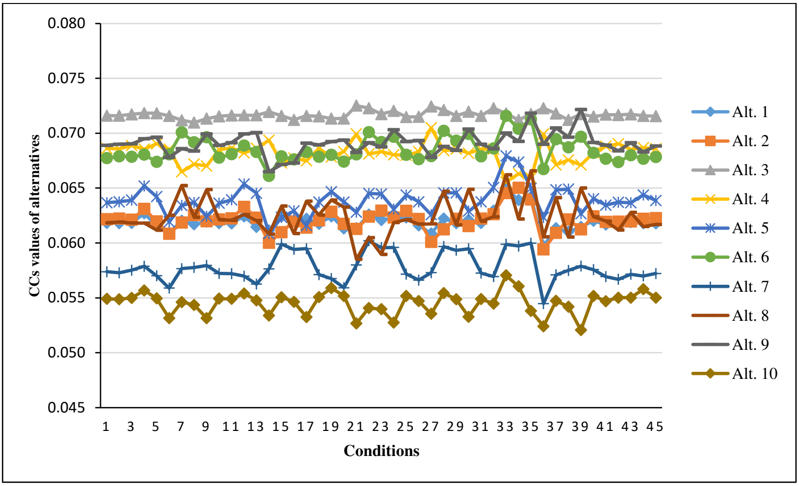



**Figure 33.** Sensitivity Analysis (Changes in CCs values produced by Fuzzy TOPSIS and associated with mutually exchange of weights of evaluation criteria produced by Fuzzy AHP based on the first aggregation method –WAM1).

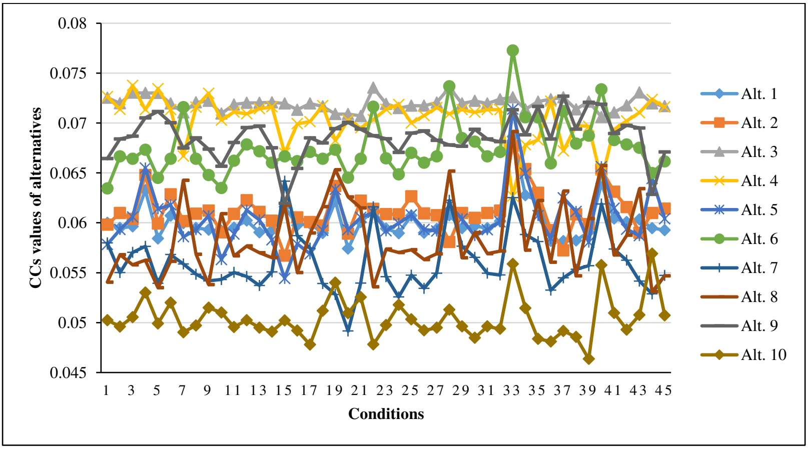



**Figure 34.** Sensitivity Analysis Outputs (Changes in CCs values produced by Fuzzy TOPSIS and associated with mutually exchange of weights of evaluation criteria produced by Fuzzy AHP based on the second aggregation method –WAM2).

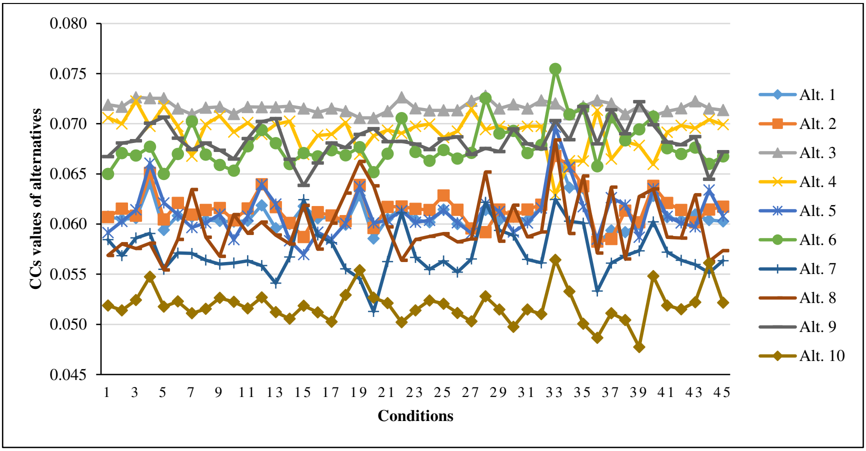



**Figure 35.** Sensitivity Analysis Outputs (Changes in CCs values produced by Fuzzy TOPSIS and associated with mutually exchange of weights of evaluation criteria produced by Fuzzy AHP based on the third aggregation method –WAM3).

The RMSE results are illustrated in Figure 36. This figure illustrated three sets of RMSE (Set 1, Set 2 and Set 3). Each set presents RMSE calculations for CCs values produced by Fuzzy TOPSIS and associated with mutually exchange of weights of evaluation criteria produced by Fuzzy AHP and based on one of the aggregation methods (WAM1, WAM2 or WAM3).

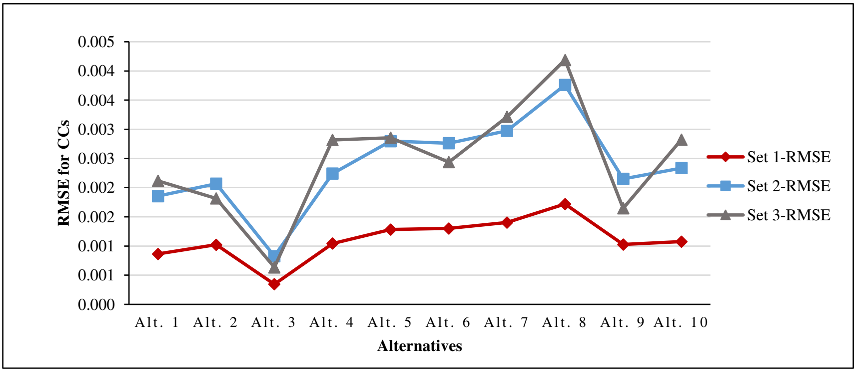



**Figure 36.** RMSE for CCs produced by sensitivity analysis with respect to the base condition (Set 1; the calculations of RMSE in association with the use of WAM1 method in Fuzzy AHP, Set 2; the calculations of RMSE in association with the use of WAM2 method in Fuzzy AHP, Set 3; the calculations of RMSE in association with the use of WAM3 method in Fuzzy AHP).

### 4.1.4 Summary of application of different MCDM techniques with regard to nominate and rank the best water loss management strategies

Table 13 displays the summary of all applied MCDM techniques (i.e. the two traditional AHP techniques: AHP-GMM and AHP-WAMM, the three Fuzzy AHP techniques based on the extent analysis Fuzzy AHP: FAHP-WAM1, FAHP-WAM2 and FAHP-WAM3, modified Fuzzy AHP, and the three integrated Fuzzy AHP-Fuzzy TOPSIS techniques).

**Table 13.** Distribution of global priority weights of alternatives and their ranking by all applied MCDM techniques

| | Alternatives | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Alt. 1** | **Alt. 2** | **Alt. 3** | **Alt. 4** | **Alt. 5** | **Alt. 6** | **Alt. 7** | **Alt. 8** | **Alt. 9** | **Alt. 10** |
| **Technique** | Priority weights **(Ranking)** | | | | | | | | | |
| **AHP-GMM** (Section 2.1.2 & Section 4.1.1) | 10.40% **(6)** | 7.85% **(7)** | 15.52% **(1)** | 14.90% **(2)** | 12.98% **(3)** | 11.12% **(5)** | 6.82% **(8)** | 4.72% **(9)** | 12.25% **(4)** | 3.43% **(10)** |
| **AHP-WAMM** (Section 2.1.2 & Section 4.1.1) | 10.59% **(6)** | 8.64% **(7)** | 14.94% **(1)** | 13.67% **(2)** | 13.22% **(3)** | 11.13% **(5)** | 6.63% **(8)** | 4.52% **(9)** | 13.07% **(4)** | 3.59% **(10)** |
| **FAHP-WAM1** (Section 2.1.3 & Section 4.1.2) | 10.19% **(6)** | 8.88% **(9)** | 11.16% **(1)** | 10.98% **(4)** | 11.10% **(2)** | 10.65% **(5)** | 9.84% **(7)** | 9.07% **(8)** | 11.00% **(3)** | 7.15% **(10)** |
| **FAHP-WAM2** (Section 2.1.3 & Section 4.1.2) | 11.01% **(6)** | 8.35% **(7)** | 13.95% **(2)** | 14.03% **(1)** | 12.79% **(3)** | 12.04% **(5)** | 7.90% **(8)** | 5.07% **(9)** | 12.26% **(4)** | 2.61% **(10)** |
| **FAHP-WAM3** (Section 2.1.3 & Section 4.1.2) | 10.33% **(6)** | 7.61% **(8)** | 14.34% **(2)** | 14.63% **(1)** | 13.10% **(3)** | 11.92% **(5)** | 8.10% **(7)** | 5.56% **(9)** | 12.10% **(4)** | 2.32% **(10)** |
| **Modified FAHP** (Section 2.1.3 & Section 4.1.2) | 9.64% **(6)** | 7.96% **(8)** | 14.39% **(1)** | 14.27% **(2)** | 13.03% **(3)** | 11.36% **(5)** | 8.00% **(7)** | 5.81% **(9)** | 11.79% **(4)** | 3.76% **(10)** |
| **FAHP-WAM1-FTOPSIS*** (Section 2.1.4 & Section 4.1.3) | 9.67% **(8)** | 9.74% **(6)** | 11.20% **(1)** | 10.73% **(3)** | 9.98% **(5)** | 10.63% **(4)** | 8.96% **(9)** | 9.70% **(7)** | 10.80% **(2)** | 8.59% **(10)** |
| **FAHP-WAM2-FTOPSIS*** (Section 2.1.4 & Section 4.1.3) | 9.66% **(6)** | 9.83% **(5)** | 11.44% **(1)** | 11.16% **(2)** | 9.62% **(7)** | 10.73% **(4)** | 9.04% **(9)** | 9.40% **(8)** | 10.88% **(3)** | 8.24% **(10)** |
| **FAHP-WAM3-FTOPSIS*** (Section 2.1.4 & Section 4.1.3) | 9.60% **(6)** | 9.84% **(5)** | 11.61% **(1)** | 11.52% **(2)** | 9.57% **(7)** | 10.76% **(4)** | 8.87% **(9)** | 9.19% **(8)** | 11.04% **(3)** | 8.01% **(10)** |
| **Mean rankings**** | **(6.22)** | **(6.89)** | **(1.22)** | **(2.11)** | **(4.00)** | **(4.67)** | **(8.00)** | **(8.44)** | **(3.44)** | **(10.00)** |
| **Final rankings**** | **(6)** | **(7)** | **(1)** | **(2)** | **(4)** | **(5)** | **(8)** | **(9)** | **(3)** | **(10)** |

*The Closeness Coefficients values (CCs) of alternatives, which are resulted from the application of the integrated methodology of Fuzzy AHP-Fuzzy TOPSIS and indicate the importance of the alternative, are normalized based on their original values displayed in Figure 31.

**The mean/average ranking method is applied herein to integrate the outcomes of all applied MCDM techniques and later, the final order of each alternative is derived.

## 4.2 Discussion of outcomes of application of different MCDM techniques to identify the proper water loss management strategies

### 4.2.1 Application of traditional Analytic Hierarchy Process (AHP)

By applying a soft MCDM technique (i.e. AHP method), it was possible to structure the decision problem in a comprehensive and an understandable mode. This approach enabled DMs and participated experts to incorporate their preferences and tradeoffs over the subcomponents of the decision problem in a more comprehensive way. By reviewing the preferences of each group of DMs towards the main criteria (level 2-Figure 8), which are displayed in Figure 19, it is well noticed that for the DM1 who represents the interests of economic and tariff department at Palestinian Water Authority (PWA), the trend was to promote first the socio-economic aspects with a percentage of 56%, followed by economic aspects with a value of 26%. This trend is compatible with the mission of this department that focuses on social and economic aspects in the water sector. The priorities of DM2, who represents the interests of water control directorate at PWA, at the main criteria level were devoted first to the economic aspects 66%, followed by the environmental aspects 20%.

The focus of DM3, who represents the interests of environmental groups, was mainly on the environmental aspects by assigning a weight of 48% for them, followed by 33% for the socio-economic aspects (Figure 19). Their trend is in agreement with their profile which is dedicated to develop and protect water and environmental resources as well as to ensure that all communities have access to water services in an affordable way. The most leading criteria from the viewpoint of DM4, who represents the concerns of water supply and sanitation department, were the economic issues in the front with a percentage of 69%, followed distantly by closed percentages for technical and environmental issues (Figure 19). Generally, the economic theme comprises the most critical aspect in any strategy to manage water losses at utility level. Water utilities, particularly in the developing countries, are in no position to bear rising of operational and maintenance costs, and capital costs of any proposed solutions to reduce water losses.

At the alternatives level as shown in Figure 21, the differentiation was clear in the performance of each group of DMs in terms of setting priorities. For the DM1, the most preferred alternative was Alt. 9 which comprises the employing of advanced techniques, while for the DM2 and DM4, the most preferred alternative was Alt. 3 which comprises the adoption of strategies to control operational pressure. This alternative also occupied advanced positions for DM1 and DM3.

Looking at preferences at individual level of DMs or at group level after the aggregation of preferences for all groups of DMs, it is noticed that the alternatives which are concerned with pressure management (Alt. 3), establishing district metered areas (Alt. 4), and utilizing advanced techniques (Alt. 9) gained high priorities in the ranking of alternatives. The focus on pressure management alternative (Alt. 3) is compatible with the strategy of Nablus municipality to restructure and rehabilitate NWDS by following a phased strategy planned to be completed by the year 2025. This strategy comprises the establishment of 27 pressure zones to maintain a range of pressure between 3 bars to 10 bars, and the pressure in the district zones will be controlled where necessary by using pressure reducing valves (PRV) (WSSD 2009).

The pivotal motive behind this planned strategy is the insufficient definition of pressure zones associated with the following factors: high differences in the altitudes which effect water pressure to reach excessive levels, leading ultimately to high physical water losses with more than ten service connections breaks daily, and the overrated pumping facilities associated with the intermittent supply that cause over pressure and consequently increase the pipe bursts, and the malfunction of water meters (WSSD 2009).

The least preferred alternatives in the overall preferences were, as shown in Figure 21, Alt. 8 (control of illegal use of water services) and Alt. 10 (public awareness and educational campaigns), which also gained least attention at individual levels. This result may be explained by the need to secure the customers' needs of water as a first priority and later it is possible to switch to these alternatives to improve and develop the process of managing water losses.

The sensitivity analysis results, which has been conducted to check the stability intervals in association with changes in the priority weights of main criteria (level 2-Figure 8), showed that the socio-economic main criterion has the highest stability interval (62.2%) with a range from 7% to 69.2%. It is followed by economic main criterion with a stability interval of 25.3%, technical main criterion with a stability interval of 18%, and lastly it was the environmental main criterion with a stability interval of 14.2%. This indicates that the ranking of alternatives will be less sensitive, more robust, with respect to changes in socio-economic main criterion first, followed by changes in priority weights of economic, technical and environmental main criteria, respectively.

### 4.2.2 Application of Fuzzy AHP techniques and comparative analysis between AHP and Fuzzy AHP techniques

Figure 22 shows the priority weights of the main criteria for all applied MCDM techniques (i.e. the traditional AHP techniques and the Fuzzy AHP techniques). Regardless the use of different methods, the main criteria maintained their ranking (economic > environmental > socio-economic > technical). One exception was the case of employing AHP-WAMM technique (economic > socio-economic > environmental > technical) but with priority weights of 25% for the socio economic criterion and 23% for the environmental criterion, which are almost similar. The strongest variation in the results of the priority weights was found for the technical aspects which attracted the least priority by all techniques. This could be attributed to the use of different aggregation methods. A very high level of convergence was reached for the environmental aspects. The priority weights of this criterion were all around 25%. The level of convergence for the socio-economic aspects was nearly similar as in case of the environmental aspects. There is also a level of convergence in the results of the priority weights of economic aspects produced by all techniques with exception of FAHP-WAM1. The FAHP-WAM1 technique uses the minimum, average and maximum evaluations of DMs to represent the lowest, most and highest possible values, respectively, in the aggregated matrix.

Figure 22 also shows that the technical main criterion value was distorted to zero in case of employing FAHP-WAM2 technique. This case of nulling a criterion's weight occurs when a large difference between the synthetic extents of two criteria is existing. Moreover, this could mean that no intersection between their synthetic extents had occurred and in turn the degree of possibility will be zero (Lima Junior *et al.* 2014). In the present case, the values of synthetic extent in the form of TFNs for technical and economic criteria were (0.046, 0.095, 0.212) and (0.241, 0.451, 0.824), respectively. As there is no intersection between the two values, the degree of possibility of the technical criterion will be null and consequently its priority weight will be zero.

As shown in Figure 23, which displays the local priority weights of evaluation criteria, the problem of null weights has also appeared at evaluation criteria level during the application of FAHP-WAM2 and FAHP-WAM3 techniques and for the same set of evaluation criteria (i.e. Benefit period (EC4-MC1), Energy saved (EC6-MC2) and Flexibility of alternative (EC8-MC3)). The previous two techniques are using the average technique and the geometric mean over the TFNs values, respectively. As indicated by Lee (2015), the chosen of the most proper method to synthesize the evaluations of DMs should be based on its performance of generating rational outcomes such as not producing too much null data.

The different used techniques showed different performance at the level of evaluation criteria as shown in Figure 24, which displays the global priorities of evaluation criteria. The generation of revenue (EC1-MC1) and water preservation and reduction of wastes (EC5-MC2) evaluation criteria maintained top positions by the most of applied techniques. Otherwise, the benefit period (EC4-MC1) and the flexibility of proposed alternatives (EC8-MC3) evaluation criteria earned the lowest priority weights by most of used techniques.

As shown in Figure 25, the application of the two traditional AHP techniques resulted in similar rankings of the alternatives (Alt. 3: pressure management> Alt. 4: establishment of district metered areas> Alt. 5: asset management> Alt. 9: utilizing advanced techniques> Alt. 6: replacement of water meters> Alt. 1: active leakage control> Alt. 2: passive leakage control> Alt. 7: improving quality level of repairs> Alt. 8: control of illegal use> Alt. 10: public awareness). The ranking that resulted from applying the modified FAHP is nearly similar to the traditional AHP with mutual exchange between "improving quality level of repairs" (Alt. 7) and "passive leakage control" (Alt. 2). "Pressure management" (Alt. 3) was ranked in the top position by most of the applied techniques. The least preferred alternatives in all cases was "public awareness" (Alt. 10).

Independent from the MCDM technique, the set of alternatives Alt. 3, Alt. 4, Alt. 5 and Alt. 9 have gained high priorities. This is attributed to a well-established knowledge about the robustness of these alternatives in water loss management. Therefore, most of the DMs' preferences related to these alternatives correspond with each other, and hence the differences in the ranking resulting from the differences related to the different aggregation methods or AHP methods were negligible. Further the nomination of "pressure management" (Alt. 3) as the alternative with the highest priority was strongly related to the boundary conditions of the case study as pointed out previously by Zyoud *et al.* (2016b) and Zyoud *et al.* (2016a).

Figures 26 and 27 display the RMSE values calculated from the priority weights of the main criteria, the evaluation criteria and the alternatives of the Fuzzy AHP techniques with respect to the two traditional AHP techniques (AHP-GMM and AHP-WAMM). These calculations are carried out to identify the degree of deviations of outcomes of different techniques to the reference results of the traditional AHP techniques. As there was a large agreement between the outcomes of the traditional AHP techniques themselves, the RMSE comparisons between the fuzzy AHP techniques and the two traditional AHP techniques shown in Figure 26 and Figure 27 led to nearly the same results. For the main criteria, the RMSE values vary strongly between different Fuzzy AHP techniques and between the criteria themselves. The RMSE values calculated at evaluation criteria level between a certain Fuzzy AHP technique and the traditional AHP techniques show only little differences. At all levels of the decision matrix the modified FAHP technique showed the lowest RMSE to the traditional AHP.

As shown in Figure 26 and Figure 27, the highest values of RMSE were reached for the environmental and technical main criteria for FAHP-WAM1, FAHP-WAM2 and FAHP-WAM3 techniques. This is attributed to the issue of distorting the values of priority weights of some evaluation criteria that are branching out from environmental and technical main criteria to low or even zero values (i.e. the distortion of values of priority weight of EC6-MC2 and EC8-MC3). In the meantime, they are overestimating the values of other evaluation criteria that are branching out from environmental and technical main criteria (i.e. the overestimating of values of priority weights of EC5-MC2 and EC7-MC3). This, in turn, has increased the margin of errors in RMSE values.

As shown in Table 10, which displays the calculations of Spearman Correlation Coefficient ($R$), the value of $R$ reached values between 0.8909 and 1. This indicates a nearly perfect association between the different techniques. There is no significant difference in ranks obtained between different techniques. The two traditional AHP techniques are perfectly correlated with each other. The modified FAHP technique had the highest correlation (0.9879) with each of the two traditional

AHP techniques and FAHP-WAM3, followed by its correlation with FAHP-WAM2 technique. Consequently, it is possible to consider the modified FAHP, a technique that has high reliability compared to the other Fuzzy AHP techniques.

The results of the sensitivity analysis which has been conducted over Fuzzy AHP techniques showed that, when the priority weights of main criteria have been changed, each in turn, from 0 to 1, a noticeable change in the ranks of alternatives can be seen. It is clear as shown in Figure 28.A and Figure 28.B, which display the changes in alternatives' ranking in association with changes in weights of economic and environmental main criteria in the modified FAHP, that the rank reversal of alternatives was higher than in case of changes in association with changes in weights of technical and socio-economic main criteria (Figure 28.C and Figure 28.D). The rank reversal of alternatives was less appeared in association with changes in weights of socio-economic main criterion compared to the outcomes produced in association with changes in weights of other main criteria. This case was the same as that in traditional AHP technique, the socio-economic criterion which is ranked three among the four main criteria by AHP-GMM technique had shown the highest stability interval compared to the other main criteria. This indicates that it has the highest flexibility in terms of changing its weight without affecting the ranking of alternatives. The least preferred alternative, Alt. 10, was the most stable alternative and showed less sensitivity to changes in weights of main criteria. The same performance was attained for the other methods of Fuzzy AHP as in the **Appendix G**.

### 4.2.3 Application of an integrated methodology of Fuzzy AHP and Fuzzy TOPSIS techniques

As explained in details in **Section 2.1.4**, the employing of an integrated methodology of Fuzzy AHP and Fuzzy TOPSIS in the process of prioritizing a set of alternatives within the water loss management framework was motivated by the adequacy and efficiency of this methodology in handling this decision problem. The extent analysis Fuzzy AHP method was employed to produce the priority vector of weights of main and evaluation criteria located in level 2 and level 3–Figure 8. As it is well noticed, the employing of Fuzzy AHP at these levels requires a maximum number of evaluations of six (i.e. there is a need for six evaluations to make tradeoffs among main criteria located in level 2-Figure 8 with respect to the overall goal in level 1-Figure 8, there is a need also for six evaluations to make tradeoffs among evaluation criteria in level 3-Figure 8 that are belonging to economic main criterion in level 2-Figure 8, while for other evaluation criteria, there is a need for one tradeoff among each set of two evaluation criteria with respect to their own main criterion). The employing of Fuzzy TOPSIS method to evaluate the performance of alternatives located in level 4-Figure 8 with respect to evaluation criteria in the upper level was essential in reducing the required evaluations. This, in turn, assists DMs and experts to easily process the required evaluations and reduces the complexity of computations.

Figure 29 shows that in terms of the main criteria, the economic and technical, but also the socio economic aspects are preferred by the DMs compared to environmental aspects. For instance, for the WAM1 aggregation method, the economic and technical aspects both achieved a percentage of approx. 30%. The socio-economic aspects achieved a percentage of 27%, while the environmental aspects attached the least attention, with a percentage of 10%. The aggregation methods WAM1, WAM2 and WAM3 generated priority weights that differ from each other (Figure 29). Regardless the application of the different aggregation methods, the main criteria maintained their ranking (economic > technical > socio-economic > environmental). The application of WAM2 and WAM3 led to a distortion of the weight of the environmental aspects to zero.

The rather small attention for the environmental aspects can be explained by the absence of environmental groups in this evaluation process. Additionally, their absence causes changes in the ranking of main criteria compared to previous works that employed the AHP and Fuzzy AHP approaches (i.e. the environmental aspects exchanged its position in the second place with the technical aspects). This is an indicator of the importance of incorporating as much as possible of all stakeholders who have interests in the decision problem with an aim of gaining a comprehensive and consensus evaluation. As in the previous works, the economic criterion was the predominant. In the field of water loss minimization, economics generally play a pivotal role. For the policy makers, the assuring of the economic viability of the proposed strategies is one of their core interests.

Figure 30 shows the results of the generated local weights at the evaluation criteria level. It can be seen that, the evaluation criterion EC8-MC3, which is related to the flexibility of the alternative, attracted the highest priority. It is followed by EC9-MC4, which stands for the affordability of the alternative and EC6-MC2, the potential of the alternative to save energy. Additionally EC5-MC2, which measures the ability of the alternative to maximize the water savings and EC10-MC4 which measures the ability of the alternative in improving water quality have turned out to be of high relevance for the DMs as well. For the WAM1 aggregation method all these five evaluation criteria achieved nearly the same weight. While for WAM2 and WAM3 the values of their priority weights differ from each other. Despite the change in values, the criteria maintained their absolute ranking position, regardless of which aggregation method was applied.

Figure 31 shows the global weights of evaluation criteria. At this evaluation level, the EC8-MC3 evaluation criterion maintained its position for all aggregation methods, while for the other criteria the priority ranking changed. Additionally, the priority weights of the evaluation criteria related to environmental issues have distorted to zero for WAM2 and WAM3 as a result of multiplication by zero, resulting from the main criteria weights.

Figure 32 shows the values of Closeness coefficients (CCs), which represent the importance of the different alternatives. For instance it can be noticed that alternative Alt. 3, which is related to managing of pressure in water distribution systems, has achieved the highest importance. This result was obtainable for all three methods of aggregation. Furthermore, alternative Alt. 6 which is related to replacement of water meters; alternative Alt. 7 which is related to improving the quality of repairs and minimizing the required time to repair the defects, and alternative Alt. 10, which is concerning with public awareness and educational campaigns, have maintained their rankings in the fourth, ninth and last positions respectively in all aggregation methods. The alternatives of establishing district metered areas (Alt. 4), and utilizing advanced techniques (Alt. 9) occupied advanced positions after the alternative of managing pressure (Alt. 3). Alt. 4 and Alt. 9 exchanged their positions, which are the second and the third, when different aggregation methods were used. Alternative Alt. 3 recorded the highest efficiency rate, while Alt. 10 recorded the least one (Figure 32).

As explained previously, the importance of pressure management stems from its potential to ensure sufficient and efficient water supply to consumers. In the meantime, it is able to reduce unnecessary or excess pressures that contribute to unnecessarily increase of leakage from water distribution systems. In our case study, this strategy has received a wide attention among other strategies due to the internal conditions that characterized NWDS. The benefits of applying pressure management strategy are beyond the benefits gained by reducing leakage and bursts. These benefits are also expanded to advantage demand and asset management.

These outputs confirm the essential role of these alternatives in implementing successfully an integrated and scalable strategy in a long term perspective. This will eliminate water losses in NWDS and will contribute in restructuring the network. Furthermore, it will improve the control over the rapid demand growth that combines with scarcity in supplies.

The alternative of public awareness and educational campaigns that could be of advantage in water conservation attracted not much attention. This could be justified, as explained previously, by the necessity to provide and secure the essential needs of water supply to the consumers as a primarily manner. Subsequently, it will be convenient to adopt alternatives like public awareness and eliminate illegal use of water services within a framework of reducing water losses.

The sensitivity analysis outputs (Table 12 and Figure 33), which has been conducted in association with applying the WAM1 aggregation method, showed that alternative Alt. 3, which has the highest CCs value in the original condition, has saved its position in forty three imposed conditions when weights of evaluation criteria were exchanged mutually. It has lost its position for the benefit of alternative Alt. 9 in the combination conditions number thirty five and thirty nine. In the first case, it is occurred when the evaluation criteria EC9-MC4 and EC5-MC2 exchanged their positions. In the second case, it was when EC9-MC4 and EC6-MC2 exchanged their positions. The alternative Alt. 10, which attracted the least value of $CC_s$, has maintained its position in all cases as the least preferred alternative. The alternative Alt. 7 which attracted the position before the last one maintained its position with the exception of one case. In this case it has exchanged its position with Alt. 8 when EC3-MC1 and EC9-MC4 exchanged their positions. For the other alternatives, a noticeable changes were documented in their $CC_s$ values that associated with the mutually exchange of weights of evaluation criteria. As it is noticed, the strongest and weakest alternatives in terms of $CC_s$ values were less sensitive to changes in weights of evaluation criteria in comparison with moderate alternatives. The ranking of alternatives was less stable and more sensitive for the other two aggregation methods (i.e. WAM2 and WAM3) as shown in Figure 34 and Figure 35.

It was noticed that the employing of different aggregation methods in Fuzzy AHP lead to differences in outputs in terms of priority weights and consequently in values of CCs in Fuzzy TOPSIS. These differences are related to using different mathematical functions. Additionally, if different fuzzy fundamental scales have to be used, there will be differences in computed priority weights. In our case study, the outputs in terms of priority weights; CCs values of alternatives and robustness of sensitivity analysis results were more satisfactory for the first proposed aggregation method (WAM1). Furthermore, the calculations of RMSE for CCs values (Figure 36) showed least errors in combination with the use of WAM1 as aggregation method in Fuzzy AHP. The Total RMSE values were (0.011; when WAM1 was used), (0.023; when WAM2 was used) and (0.024; when WAM3 was used). This indicates that the outcomes in association with applying WAM1 as aggregation approach in used Fuzzy AHP method resulted in more robust outcomes in terms of ranking alternatives.

### 4.2.4 Summary of application of different MCDM techniques with regard to nominate and rank the best water loss management strategies

Regardless the application of different MCDM techniques, the most applied techniques were in agreement in terms of ranking pressure management (Alt. 3), establishment of district metered areas (Alt. 4) and employing of advanced techniques to fix the leaks and predict failures in WDNs (Alt. 9) as the most potential alternatives to manage water losses in the examined case study. These alternatives are widely acknowledged as effective and robust strategies in managing water losses in WDNs. Furthermore, all applied MCDM techniques were in agreement towards the nomination of public awareness and educational campaigns (Alt. 10) as the least preferred alternative. By applying the mean ranking method to integrate the outcomes of all applied MCDM techniques in terms of ranking alternatives, the final order of ranking alternatives was: Alt. 3 > Alt. 4 > Alt. 9 > Alt. 5 > Alt. 1 > Alt. 2 > Alt. 7 > Alt. 8 > Alt. 10.

The non-significant difference between the different MCDM techniques in terms of ranking alternatives, particularly for the most and least preferred alternatives, is an indicator for the robustness of the developed water loss management decision making framework. This indicates that the structuring of the decision problem was in a comprehensive and clear way which facilitated the duty of DMs to incorporate their evaluations. Therefore, most of the DMs' preferences related to these alternatives correspond with each other, and hence the differences in the ranking resulted from employing different AHP techniques, different aggregation methods in Fuzzy AHP techniques and/or the integrated methodology of Fuzzy AHP and Fuzzy TOPSIS were negligible. Furthermore, and despite the fact that the number of participated experts in the evaluation of different decision elements of the water loss management framework was different from one technique to another, the differences were non-significant as explained previously. This additionally indicates the robustness of the developed framework and the followed methodology in structuring the decision problem.

# 5 Results and discussion of application of the simulation based multi-criteria decision making framework for evaluation of WLRI in water distribution systems

This section is structured as follows: First, the outcomes of the application of the simulation based multi-criteria decision making framework to evaluate the WLRI in WSNs are presented. Second, a discussion of the outcomes that are resulted from the application of WLRI evaluation framework on a case study is carried out.

## 5.1 Results of application of the simulation based multi-criteria decision making framework for evaluation of WLRI in water distribution systems

### 5.1.1 Data required to assign the weights of elements of WLRI framework

As stated previously, the relative importance of the various elements of the developed framework is articulated through weights. These weights are established with the aid of relevant experts in the field where the modified Fuzzy AHP is applied as explained in **(Section 2.1.3.1)** and **(Section 2.2.2)**. As explained is the case study section, four experts were enrolled in this work. The experts were asked to undertake a series of pairwise compassions and to assign linguistic evaluations based on the scale displayed in Table 3–**Section 2.1.3.1** at each level of the framework-Figure 14 (i.e. tradeoffs among the basic factors located in level 1-Figure14 with respect to their own category in the upper level, etc.). Their evaluations are based on answering the question: what is the strength or the impact of the factor compared to other factors in the same category in contributing to the rate of water losses in pipes of WSNs. To illustrate how the procedure is applied, the evaluations of experts towards the basic factors of physical category (Level 1-Figure 14) are displayed below for pairwise comparison matrix (PC 1.1) after their collection from the individual experts. It is followed by converting their evaluations into TFNs, and the aggregation of all evaluations to generate the final aggregated matrix. After the collection of evaluations of experts towards all levels of the framework, the methodology of modified Fuzzy AHP is followed to derive the relative importance of all factors and their categories.

| | Physical category | | Pipe diameter | Pipe material | Pipe age | Pipe length | Type of traffic | Type of road |
|---|---|---|---|---|---|---|---|---|
| **PC 1.1** (Evaluations of experts towards basic factors of physical category using linguistic terms) | Pipe diameter | Expert 1 Water utility | EI | MI | (SI)* | (MI) | MI | SI |
| | | Expert 2 Water utility | EI | (MI) | (SI) | (MI) | SI | SI |
| | | Expert 3 Scientific community | EI | EI | (SI) | EI | SI | SI |
| | | Expert 4 Scientific community | EI | EI | (SI) | (MI) | MI | MI |
| | Pipe material | Expert 1 Water utility | | EI | (SI) | (MI) | MI | SI |
| | | Expert 2 Water utility | | EI | (SI) | EI | SI | SI |
| | | Expert 3 Scientific community | | EI | (VSI) | MI | SI | VSI |
| | | Expert 4 Scientific community | | EI | (SI) | MI | SI | SI |
| | Pipe age | Expert 1 Water utility | | | EI | MI | SI | SI |
| | | Expert 2 Water utility | | | EI | SI | VSI | VSI |
| | | Expert 3 Scientific community | | | EI | SI | VSI | VSI |
| | | Expert 4 Scientific community | | | EI | SI | VSI | VSI |
| | Pipe length | Expert 1 Water utility | | | | EI | MI | SI |
| | | Expert 2 Water utility | | | | EI | SI | SI |
| | | Expert 3 Scientific community | | | | EI | SI | SI |
| | | Expert 4 Scientific community | | | | EI | MI | MI |
| | Type of traffic | Expert 1 Water utility | | | | | EI | EI |
| | | Expert 2 Water utility | | | | | EI | EI |
| | | Expert 3 Scientific community | | | | | EI | EI |
| | | Expert 4 Scientific community | | | | | EI | EI |
| | Type of road | Expert 1 Water utility | | | | | | EI |
| | | Expert 2 Water utility | | | | | | EI |
| | | Expert 3 Scientific community | | | | | | EI |
| | | Expert 4 Scientific community | | | | | | EI |

***** Input inside parentheses means that this input is reciprocal to what mentioned inside parentheses.
Note: all inputs below the diagonal of the comparison matrix will be reciprocal to the inputs above the diagonal.

| | Physical category | | Pipe diameter | Pipe material | Pipe age | Pipe length | Type of traffic | Type of road |
|---|---|---|---|---|---|---|---|---|
| **PC 1.1** (Converting of evaluations of experts towards basic factors of physical category from linguistic terms into TFNs) | Pipe diameter | Expert 1 Water utility | (1,1,1) | (1,3,5) | (1/7,1/5,1/3) | (1/5,1/3,1) | (1,3,5) | (3,5,7) |
| | | Expert 2 Water utility | (1,1,1) | (1/5,1/3,1) | (1/7,1/5,1/3) | (1/5,1/3,1) | (3,5,7) | (3,5,7) |
| | | Expert 3 Scientific community | (1,1,1) | (1,1,1) | (1/7,1/5,1/3) | (1,1,1) | (3,5,7) | (3,5,7) |
| | | Expert 4 Scientific community | (1,1,1) | (1,1,1) | (1/7,1/5,1/3) | (1/5,1/3,1) | (1,3,5) | (1,3,5) |
| | Pipe material | Expert 1 Water utility | (1/5,1/3,1) | (1,1,1) | (1/7,1/5,1/3) | (1/5,1/3,1) | (1,3,5) | (3,5,7) |
| | | Expert 2 Water utility | (1,3,5) | (1,1,1) | (1/7,1/5,1/3) | (1,1,1) | (3,5,7) | (3,5,7) |
| | | Expert 3 Scientific community | (1,1,1) | (1,1,1) | (1/9,1/7,1/5) | (1,3,5) | (3,5,7) | (5,7,9) |
| | | Expert 4 Scientific community | (1,1,1) | (1,1,1) | (1/7,1/5,1/3) | (1,3,5) | (3,5,7) | (3,5,7) |
| | Pipe age | Expert 1 Water utility | (3,5,7) | (3,5,7) | (1,1,1) | (1,3,5) | (3,5,7) | (3,5,7) |
| | | Expert 2 Water utility | (3,5,7) | (3,5,7) | (1,1,1) | (3,5,7) | (5,7,9) | (5,7,9) |
| | | Expert 3 Scientific community | (3,5,7) | (5,7,9) | (1,1,1) | (3,5,7) | (5,7,9) | (5,7,9) |
| | | Expert 4 Scientific community | (3,5,7) | (3,5,7) | (1,1,1) | (3,5,7) | (5,7,9) | (5,7,9) |
| | Pipe length | Expert 1 Water utility | (1,3,5) | (1,3,5) | (1/5,1/3,1) | (1,1,1) | (1,3,5) | (3,5,7) |
| | | Expert 2 Water utility | (1,3,5) | (1,1,1) | (1/7,1/5,1/3) | (1,1,1) | (3,5,7) | (3,5,7) |
| | | Expert 3 Scientific community | (1,1,1) | (1/5,1/3,1) | (1/7,1/5,1/3) | (1,1,1) | (3,5,7) | (3,5,7) |
| | | Expert 4 Scientific community | (1,3,5) | (1/5,1/3,1) | (1/7,1/5,1/3) | (1,1,1) | (1,3,5) | (1,3,5) |
| | Type of traffic | Expert 1 Water utility | (1/5,1/3,1) | (1/5,1/3,1) | (1/7,1/5,1/3) | (1/5,1/3,1) | (1,1,1) | (1,1,1) |
| | | Expert 2 Water utility | (1/7,1/5,1/3) | (1/7,1/5,1/3) | (1/9,1/7,1/5) | (1/7,1/5,1/3) | (1,1,1) | (1,1,1) |
| | | Expert 3 Scientific community | (1/7,1/5,1/3) | (1/7,1/5,1/3) | (1/9,1/7,1/5) | (1/7,1/5,1/3) | (1,1,1) | (1,1,1) |
| | | Expert 4 Scientific community | (1/5,1/3,1) | (1/7,1/5,1/3) | (1/9,1/7,1/5) | (1/5,1/3,1) | (1,1,1) | (1,1,1) |
| | Type of road | Expert 1 Water utility | (1/7,1/5,1/3) | (1/7,1/5,1/3) | (1/7,1/5,1/3) | (1/7,1/5,1/3) | (1,1,1) | (1,1,1) |
| | | Expert 2 Water utility | (1/7,1/5,1/3) | (1/7,1/5,1/3) | (1/9,1/7,1/5) | (1/7,1/5,1/3) | (1,1,1) | (1,1,1) |
| | | Expert 3 Scientific community | (1/7,1/5,1/3) | (1/9,1/7,1/5) | (1/9,1/7,1/5) | (1/7,1/5,1/3) | (1,1,1) | (1,1,1) |
| | | Expert 4 Scientific community | (1/5,1/3,1) | (1/7,1/5,1/3) | (1/9,1/7,1/5) | (1/5,1/3,1) | (1,1,1) | (1,1,1) |

| | Physical category | Pipe diameter | Pipe material | Pipe age | Pipe length | Type of traffic | Type of road |
|---|---|---|---|---|---|---|---|
| **PC 1.1** (Aggregation of evaluations of experts based on geometric mean operator) | Pipe diameter | (1,1,1) | (0.67,1,1.5) | (0.14,0.2,0.33) | (0.3,0.44,1) | (1.73,3.87,5.92) | (2.28,4.4,6.44) |
| | Pipe material | (0.67,1,1.5) | (1,1,1) | (0.13,0.18,0.29) | (0.67,1.32,2.24) | (2.28,4.4,6.44) | (3.41,5.44,7.45) |
| | Pipe age | (3,5,7) | (3.41,5.44,7.45) | (1,1,1) | (2.28,4.4,6.44) | (4.4,6.44,8.45) | (4.4,6.44,8.45) |
| | Pipe length | (1,2.28,3.34) | (0.45,0.76,1.5) | (0.16,0.23,0.44) | (1,1,1) | (1.73,3.87,5.92) | (2.28,4.4,6.44) |
| | Type of traffic | (0.17,0.26,0.58) | (0.16,0.23,0.44) | (0.12,0.16,0.23) | (0.17,0.26,0.58) | (1,1,1) | (1,1,1) |
| | Type of road | (0.16,0.23,0.44) | (0.13,0.18,0.29) | (0.12,0.16,0.23) | (0.16,0.23,0.44) | (1,1,1) | (1,1,1) |

The application of modified Fuzzy AHP, which has been explained in details in **(Section 2.1.3.1)**, resulted in calculation of priority weights of structure elements of WLRI framework. Table 14 displays these outcomes and the consistency test for the five evaluation matrices. The physical and operation categories gained the highest priority with a value of about 40% for each. At the basic factors level, the pipe age was the predominant in the physical category with a percentage of around 40%. Number of breaks and pressure were the predominant in operational category with values around 30%. In environmental category, the impact on public health was with high priority, 50%. The same value was reached by the density of population basic factor in the social category. The CR values for nearly all the evaluation matrices were within the acceptable thresholds (i.e. CR < 10%).

**Table 14.** Priority weights of WLRI framework elements (main categories and their basic factors) and the consistency test outputs

| Evaluation matrix | Explanation | Priority weights of WLRI framework elements | | Consistency outputs | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **Main category/basic factor** | **Priority weight** | ***n*** | **$\lambda_{max}$** | **CI** | **RI** | **CR** |
| **PC1** | Main categories evaluation matrix | Physical category<br>Operational category<br>Environmental category<br>Social category | 0.40<br>0.39<br>0.11<br>0.09 | 4 | 4.121 | 0.0404 | 0.9 | 4.49% < 10% |
| **PC1.1** | Physical category basic factors evaluation matrix | Pipe diameter<br>Pipe material<br>Pipe age<br>Pipe length<br>Type of traffic<br>Type of road | 0.160<br>0.191<br>0.381<br>0.179<br>0.046<br>0.043 | 6 | 6.626 | 0.1252 | 1.24 | 10.1% ≈ 10% |
| **PC2.1** | Operational category basic factors evaluation matrix | Pressure<br>Water Velocity<br>No. of breaks<br>Water meters<br>Average supply hours<br>Service connections | 0.285<br>0.120<br>0.288<br>0.063<br>0.172<br>0.072 | 6 | 6.528 | 0.1056 | 1.24 | 8.51% < 10% |
| **PC3.1** | Environmental category basic factors evaluation matrix | Quality of water<br>Impact on public health<br>Damage to surrounding | 0.363<br>0.502<br>0.136 | 3 | 3.065 | 0.0327 | 0.58 | 5.64% < 10% |
| **PC4.1** | Social category basic factors evaluation matrix | Type of consumption<br>Density of population<br>Public economies | 0.322<br>0.505<br>0.17 | 3 | 3.114 | 0.0571 | 0.58 | 9.84% < 10% |

## 5.1.2 Application of Fuzzy Synthetic Evaluation (FSE) technique and Ordered Weighted averaging (OWA) operators

For the application of FSE technique, this has required the collection of field data of basic factors –Level 1/Figure 14 for every pipe in each selected zone. The data are arranged in Excel sheets. A Python-based tool was developed to import these data to run FSE process with an aim of generating the WLRI/pipe. Figure 37 illustrates, as exemplification of FSE process, the steps of generating WLRI for a pipe in zone W0 with the following some major characteristics: pipe diameter (100 mm), pipe material (Galvanized steel), pipe age (16 years), pipe length (454.89 m), pressure (65 m), water velocity (0.72 m/s), supply hours (8 hrs. /day), type of consumption (Residential) and an ID 2085.

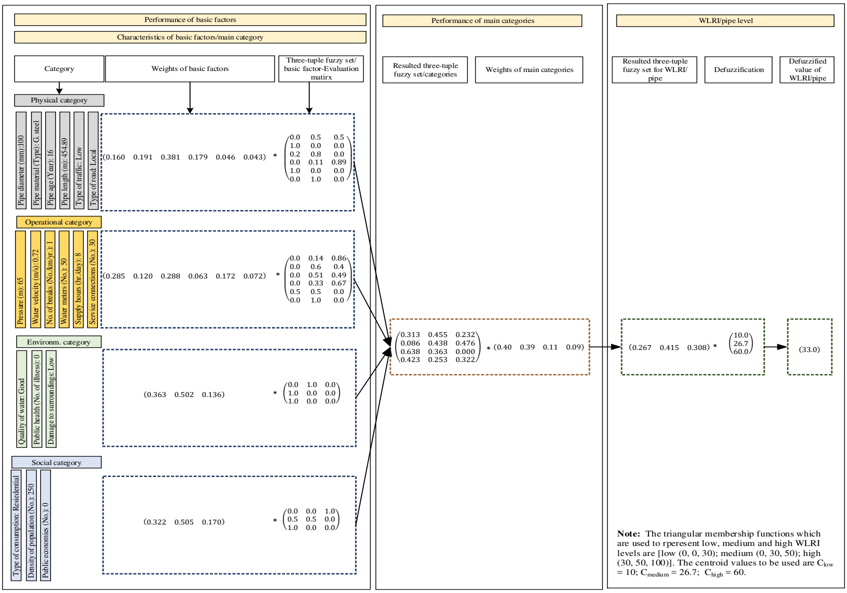



**Figure 37.** Sample of generating WLRI for a pipe with an ID 2085, Zone W0 -NWDS by FSE technique with the following some major characteristics: pipe diameter (100 mm), pipe material (Galvanized steel), pipe age (16 years), pipe length (454.89 m) and average pressure (65 m).

The resulted values of individual WLRI per each pipe from applying FSE technique have to be aggregated for each group of pipes belongs to each zone. This aggregation will generate WLRI at zone level. The aggregation will be performed by employing the OVGWA and OWALD operators, each in turn. Figure 38 displays the generated visibility graph related to zone NW0-NWDS for illustration purposes.

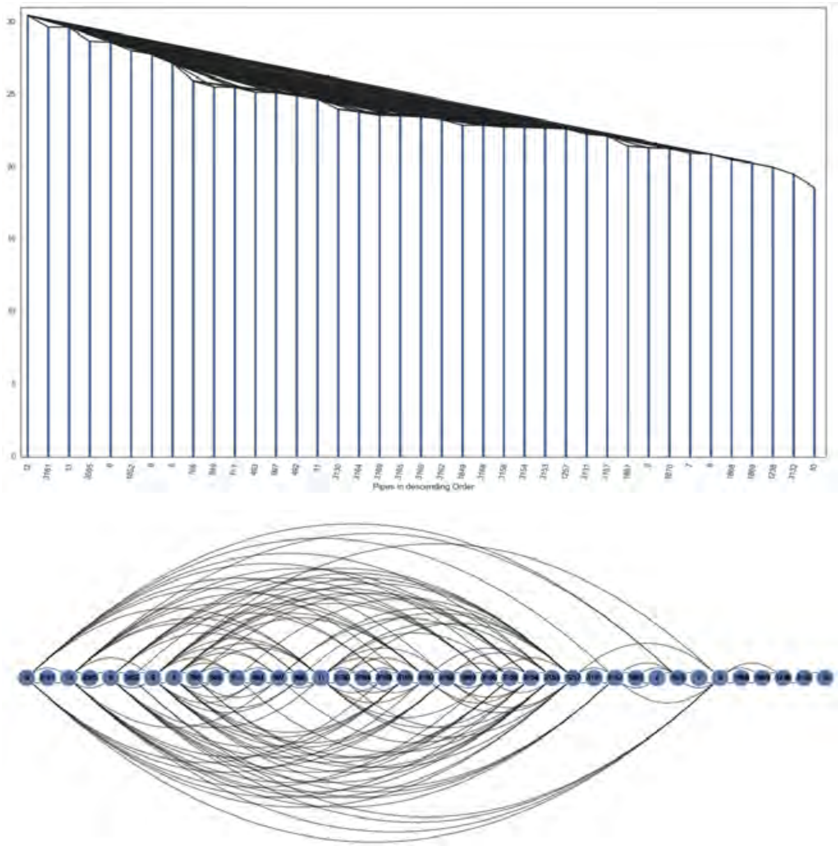



**Figure 38.** The generated visibility graph related to Zone NW0-NWDS to calculate the number of links for each node with an aim of estimating the associated weights in OVGWA operator technique.

Table 15 displays the calculations associated with the application of OVGWA and OWALD techniques as aggregation operators to calculate the WLRI of zone NW0-NWDS. The results of aggregation show that the WLRI of Zone NW0-NWDS is: 24.8% by OVGWA, and 27.3% by OWALD technique.

**Table 15.** Sample of calculation of WLRI for pipes in Zone NW0-NWDS by OVGWA and OWALD techniques

| ID of pipe | WLRI/ pipe in descending order (from FSE technique)-$a_i$ | No. of links /pipe-visibility graph in OVGWA* | $w_i$/pipe-OVGWA | ( $a_i$*$w_i$) /pipe-OVGWA | $w_i$/pipe-OWALD | ($a_i$*$w_i$) /pipe-OWALD |
|---|---|---|---|---|---|---|
| 12 | 0.3050 | 15 | 0.0455 | 0.0139 | 0.1180 | 0.0360 |
| 3161 | 0.2966 | 2 | 0.0061 | 0.0018 | 0.1042 | 0.0309 |
| 13 | 0.2966 | 20 | 0.0606 | 0.0180 | 0.0920 | 0.0273 |
| 3565 | 0.2868 | 2 | 0.0061 | 0.0017 | 0.0812 | 0.0233 |
| 6 | 0.2863 | 17 | 0.0515 | 0.0147 | 0.0717 | 0.0205 |
| 1852 | 0.2804 | 5 | 0.0152 | 0.0042 | 0.0633 | 0.0178 |
| 9 | 0.2778 | 19 | 0.0576 | 0.0160 | 0.0559 | 0.0155 |
| 5 | 0.2719 | 16 | 0.0485 | 0.0132 | 0.0494 | 0.0134 |
| 766 | 0.2596 | 8 | 0.0242 | 0.0063 | 0.0436 | 0.0113 |
| 549 | 0.2554 | 3 | 0.0091 | 0.0023 | 0.0385 | 0.0098 |
| P-1 | 0.2551 | 8 | 0.0242 | 0.0062 | 0.0340 | 0.0087 |
| 493 | 0.2516 | 4 | 0.0121 | 0.0030 | 0.0300 | 0.0075 |
| 997 | 0.2514 | 11 | 0.0333 | 0.0084 | 0.0265 | 0.0067 |
| 492 | 0.2491 | 7 | 0.0212 | 0.0053 | 0.0234 | 0.0058 |
| 11 | 0.2473 | 19 | 0.0576 | 0.0142 | 0.0206 | 0.0051 |
| 3130 | 0.2400 | 6 | 0.0182 | 0.0044 | 0.0182 | 0.0044 |
| 3164 | 0.2380 | 5 | 0.0152 | 0.0036 | 0.0161 | 0.0038 |
| 3169 | 0.2357 | 6 | 0.0182 | 0.0043 | 0.0142 | 0.0033 |
| 3165 | 0.2352 | 10 | 0.0303 | 0.0071 | 0.0125 | 0.0029 |
| 3160 | 0.2346 | 13 | 0.0394 | 0.0092 | 0.0111 | 0.0026 |
| 3162 | 0.2331 | 13 | 0.0394 | 0.0092 | 0.0098 | 0.0023 |
| 1849 | 0.2291 | 2 | 0.0061 | 0.0014 | 0.0086 | 0.0020 |
| 3168 | 0.2290 | 12 | 0.0364 | 0.0083 | 0.0076 | 0.0017 |
| 3156 | 0.2278 | 9 | 0.0273 | 0.0062 | 0.0067 | 0.0015 |
| 3154 | 0.2276 | 13 | 0.0394 | 0.0090 | 0.0059 | 0.0014 |
| 3153 | 0.2271 | 15 | 0.0455 | 0.0103 | 0.0052 | 0.0012 |
| 1257 | 0.2265 | 19 | 0.0576 | 0.0130 | 0.0046 | 0.0010 |
| 3131 | 0.2227 | 2 | 0.0061 | 0.0013 | 0.0041 | 0.0009 |
| 3157 | 0.2214 | 11 | 0.0333 | 0.0074 | 0.0036 | 0.0008 |
| 1867 | 0.2148 | 3 | 0.0091 | 0.0020 | 0.0032 | 0.0007 |
| 2 | 0.2135 | 3 | 0.0091 | 0.0019 | 0.0028 | 0.0006 |
| 1870 | 0.2130 | 7 | 0.0212 | 0.0045 | 0.0025 | 0.0005 |
| 7 | 0.2098 | 2 | 0.0061 | 0.0013 | 0.0022 | 0.0005 |
| 8 | 0.2089 | 12 | 0.0364 | 0.0076 | 0.0019 | 0.0004 |
| 1868 | 0.2050 | 2 | 0.0061 | 0.0012 | 0.0017 | 0.0004 |
| 1869 | 0.2030 | 3 | 0.0091 | 0.0018 | 0.0015 | 0.0003 |
| 1238 | 0.2001 | 3 | 0.0091 | 0.0018 | 0.0013 | 0.0003 |
| 3132 | 0.1952 | 2 | 0.0061 | 0.0012 | 0.0012 | 0.0002 |
| 10 | 0.1860 | 1 | 0.0030 | 0.0006 | 0.0010 | 0.0002 |
| | | **Total no. of links = 330** | | **24.8%** | | **27.36%** |

* refer to Figure 38

Figure 39 displays the values of aggregated WLRI for the ten selected zones in NWDS by OVGWA and OWALD techniques.

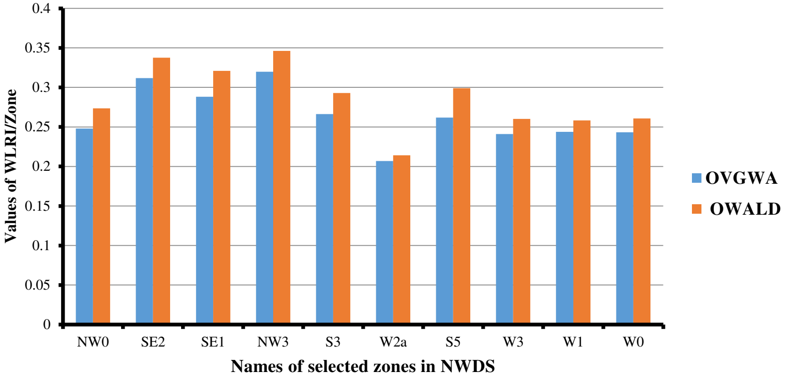



**Figure 39.** Illustration of values of WLRI/ Zone generated by OVGWA and OWALD aggregation techniques.

### 5.1.3 Application of scenario analysis and Monte Carlo simulation analysis

The results of application of scenario analysis are displayed in Table 16, Figure 40 and Figure 41. These results are outcomes of mutual exchange of main categories in Level 2-Figure 14 and from the assumption of equal weights of main categories, followed by the calculations of individual WLRI per each pipe and the aggregation of these individual WLRI values by OVGWA and OWALD techniques, each in turn. In Table 16, it is clear that the changes in ranking zones were less sensitive to the changes of weights of main categories for OVGWA compared to the case of OWALD. Figure 42 displays the RMSE values of WLRI/zone with respect to original values produced by OVGWA and OWALD techniques, each in turn. The total RMSE for the OVGWA technique was 0.03295, while for the OWALD technique, it was 0.03564.

**Table 16.** Outcomes of scenario analysis (Changes in values of WLRI/zone in association with mutually exchange of weights of main categories and equal weights assumption)

| | Weights of main categories (original, mutually exchange and equal weights) | | | | | Resulted values of WLRI/Zone by OVGWA technique in association with changes in weights of main categories | | | | | | | | | | | Ranking in association with changes in weights of main categories |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conditions | Physical | Operational | Environmental | Social | | NW0 | SE2 | SE1 | NW3 | S3 | W2a | S5 | W3 | W1 | W0 | | |
| Original Condition (OC) | 0.40539 | 0.38217 | 0.11958 | 0.09286 | | 0.24803 | 0.31184 | 0.28829 | 0.31993 | 0.26631 | 0.20700 | 0.26181 | 0.24114 | 0.24388 | 0.24317 | | NW3> SE2> SE1> S3> S5> NW0> W1> W0> W3 > W2a |
| Condition no.1 (C1) | 0.38217 | 0.40539 | 0.11958 | 0.09286 | | 0.24879 | 0.31291 | 0.29097 | 0.32112 | 0.26629 | 0.20628 | 0.26268 | 0.24174 | 0.24211 | 0.24463 | | NW3> SE2> SE1> S3> S5> NW0> W0> W1> W3> W2a |
| Condition no.2 (C2) | 0.11958 | 0.38217 | 0.40539 | 0.09286 | | 0.21553 | 0.26207 | 0.25341 | 0.26150 | 0.23177 | 0.17514 | 0.22993 | 0.19370 | 0.20896 | 0.21938 | | SE2> NW3> SE1> S3> S5> W0> NW0> W1> W3> W2a |
| Condition no.3 (C3) | 0.09286 | 0.38217 | 0.11958 | 0.40539 | | 0.19792 | 0.23983 | 0.23643 | 0.24348 | 0.21634 | 0.17756 | 0.21276 | 0.19725 | 0.19486 | 0.20089 | | NW3> SE2> SE1> S3> S5> W0> NW0> W3> W1> W2a |
| Condition no.4 (C4) | 0.40539 | 0.11958 | 0.38217 | 0.09286 | | 0.21050 | 0.25538 | 0.23620 | 0.26548 | 0.22584 | 0.16583 | 0.22530 | 0.19435 | 0.21750 | 0.21028 | | NW3> SE2> SE1> S3> S5> W1> NW0> W0> W3> W2a |
| Condition no.5 (C5) | 0.40539 | 0.09286 | 0.11958 | 0.38217 | | 0.19153 | 0.24087 | 0.22291 | 0.24999 | 0.21235 | 0.16349 | 0.20612 | 0.19223 | 0.20642 | 0.19384 | | NW3> SE2> SE1> S3> W1> S5> W0> W3> NW0> W2a |
| Condition no.6 (C6) | 0.40539 | 0.38217 | 0.09286 | 0.11958 | | 0.24557 | 0.31086 | 0.28568 | 0.31850 | 0.26519 | 0.20713 | 0.26138 | 0.24193 | 0.24119 | 0.24197 | | NW3> SE2> SE1> S3> S5> NW0> W0> W3> W1> W2a |
| Condition no.7- Equal weights (C7) | 0.25000 | 0.25000 | 0.25000 | 0.25000 | | 0.20383 | 0.25208 | 0.23501 | 0.25434 | 0.22143 | 0.17107 | 0.21782 | 0.19309 | 0.20616 | 0.20154 | | NW3> SE2> SE1> S3> S5> W1> NW0> W0> W3> W2a |

| | Weights of main categories (original, mutually exchange and equal weights) | | | | | Resulted values of WLRI/Zone by OWALD technique in association with changes in weights of main categories | | | | | | | | | | | Ranking in association with changes in weights of main categories |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conditions | Physical | Operational | Environmental | Social | | NW0 | SE2 | SE1 | NW3 | S3 | W2a | S5 | W3 | W1 | W0 | | |
| Original Condition (OC) | 0.40539 | 0.38217 | 0.11958 | 0.09286 | | 0.27361 | 0.33751 | 0.32094 | 0.34619 | 0.29303 | 0.21420 | 0.29889 | 0.26017 | 0.25826 | 0.26060 | | NW3> SE2> SE1> S5> S3> NW0> W0> W3> W1 > W2a |
| Condition no.1 (C1) | 0.38217 | 0.40539 | 0.11958 | 0.09286 | | 0.27381 | 0.33960 | 0.32141 | 0.34698 | 0.29321 | 0.21534 | 0.29903 | 0.25988 | 0.25731 | 0.26067 | | NW3> SE2> SE1> S5> S3> NW0> W0> W3> W1> W2a |
| Condition no.2 (C2) | 0.11958 | 0.38217 | 0.40539 | 0.09286 | | 0.23490 | 0.29280 | 0.26539 | 0.28349 | 0.24596 | 0.18075 | 0.24932 | 0.20383 | 0.21697 | 0.22547 | | SE2> NW3> SE1> S5> S3> NW0> W0> W1> W3> W2a |
| Condition no.3 (C3) | 0.09286 | 0.38217 | 0.11958 | 0.40539 | | 0.22200 | 0.28033 | 0.25270 | 0.27542 | 0.23530 | 0.18070 | 0.23697 | 0.21497 | 0.20641 | 0.21189 | | SE2> NW3> SE1> S3> S5> NW0> W3> W0> W1> W2a |
| Condition no.4 (C4) | 0.40539 | 0.11958 | 0.38217 | 0.09286 | | 0.23638 | 0.27341 | 0.26444 | 0.28023 | 0.24761 | 0.17086 | 0.25197 | 0.21115 | 0.23065 | 0.22758 | | SE2> NW3> SE1> S5> S3> NW0> W1> W0> W3> W2a |
| Condition no.5 (C5) | 0.40539 | 0.09286 | 0.11958 | 0.38217 | | 0.22419 | 0.26072 | 0.25124 | 0.27312 | 0.23588 | 0.17074 | 0.23983 | 0.21804 | 0.21982 | 0.21306 | | NW3> SE2> SE1> S5> S3> NW0> W3> W1> W0> W2a |
| Condition no.6 (C6) | 0.40539 | 0.38217 | 0.09286 | 0.11958 | | 0.27254 | 0.33681 | 0.32020 | 0.34585 | 0.29239 | 0.21440 | 0.29815 | 0.26119 | 0.25744 | 0.25941 | | NW3> SE2> SE1> S5> S3> NW0> W3> W0> W1> W2a |
| Condition no.7- Equal weights (C7) | 0.25000 | 0.25000 | 0.25000 | 0.25000 | | 0.22614 | 0.27582 | 0.25763 | 0.27719 | 0.24048 | 0.17486 | 0.24342 | 0.21009 | 0.21722 | 0.21660 | | NW3> SE2> SE1> S5> S3> NW0> W1> W0> W3> W2a |

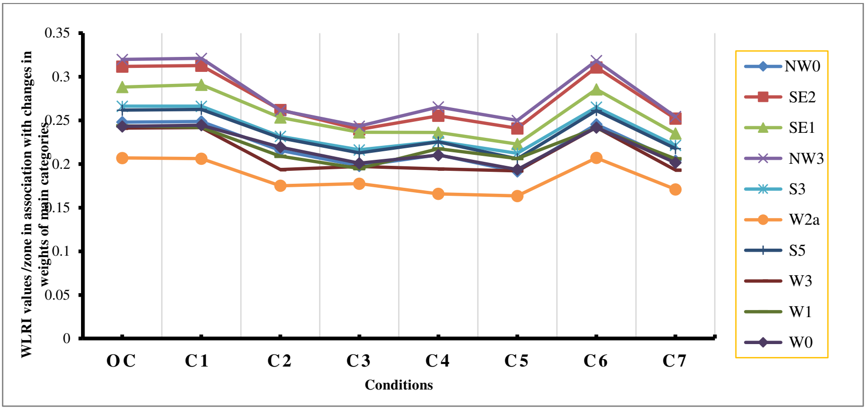



**Figure 40.** Values of WLRI/zone resulted by OVGWA technique in association with changes in weights of main categories.

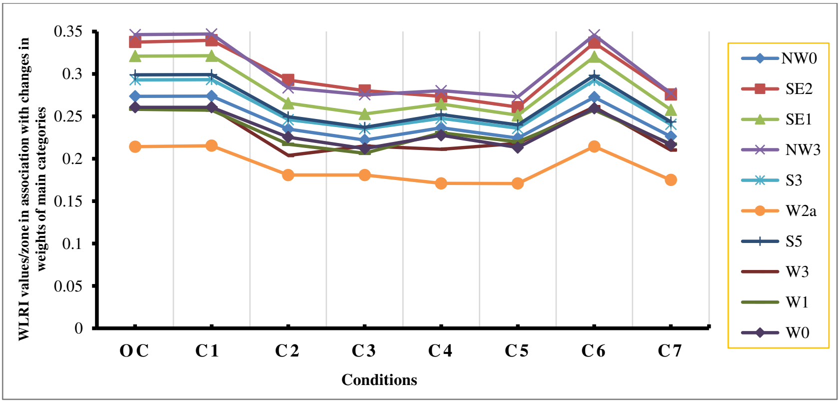



**Figure 41.** Values of WLRI/zone resulted by OWALD technique in association with changes in weights of main categories.

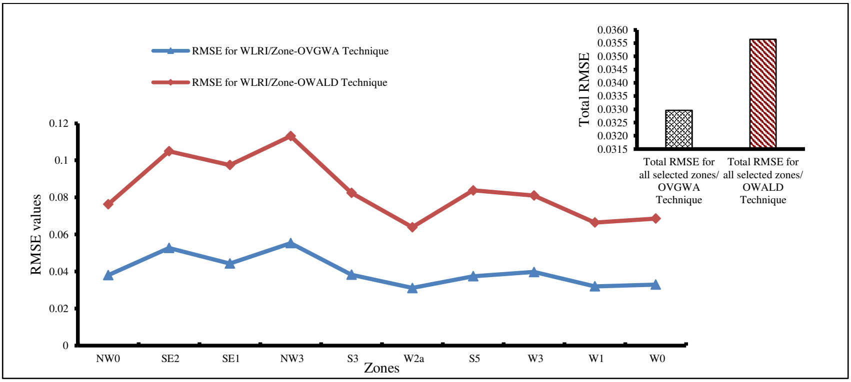



**Figure 42.** RMSE values of WLRI/zone with respect to original values produced by OVGWA and OWALD techniques.

Figure 43 displays the outcomes of the application of the Monte Carlo simulation model over the whole methodology that utilized OVGWA technique. This model used the triangular probability distribution function to convert the triangular numbers, which represent the weights of basic factors that contribute to WLRI and their categories in the form of triangular number, to random numbers. These random numbers are used to conduct the Monte Carlo simulation analysis to acquire a better understanding of the impact of uncertainty in the weights of WLRI framework elements on the outcomes, e.g. values of WLRI for zones and the ranking of zones with regard to the associated WLRI values. Based on Figure 43, it is possible to rank the zones from the one with the highest WLRI to the one with the lowest WLRI as NW3, SE2, SE1, S3, S5, NW0, W0, W3, W1, and W2a. Figure 43 shows in addition to the average values of WLRI for each zone all possible scenarios. For example, it shows that NW3 is the zone with the highest WLRI value on the average. In addition to that, it shows that there is a level of probability that SE2 and SE1 zones might have higher WLRI values than NW3. Accordingly, this gives all related information about the prioritization of different zones for the users.

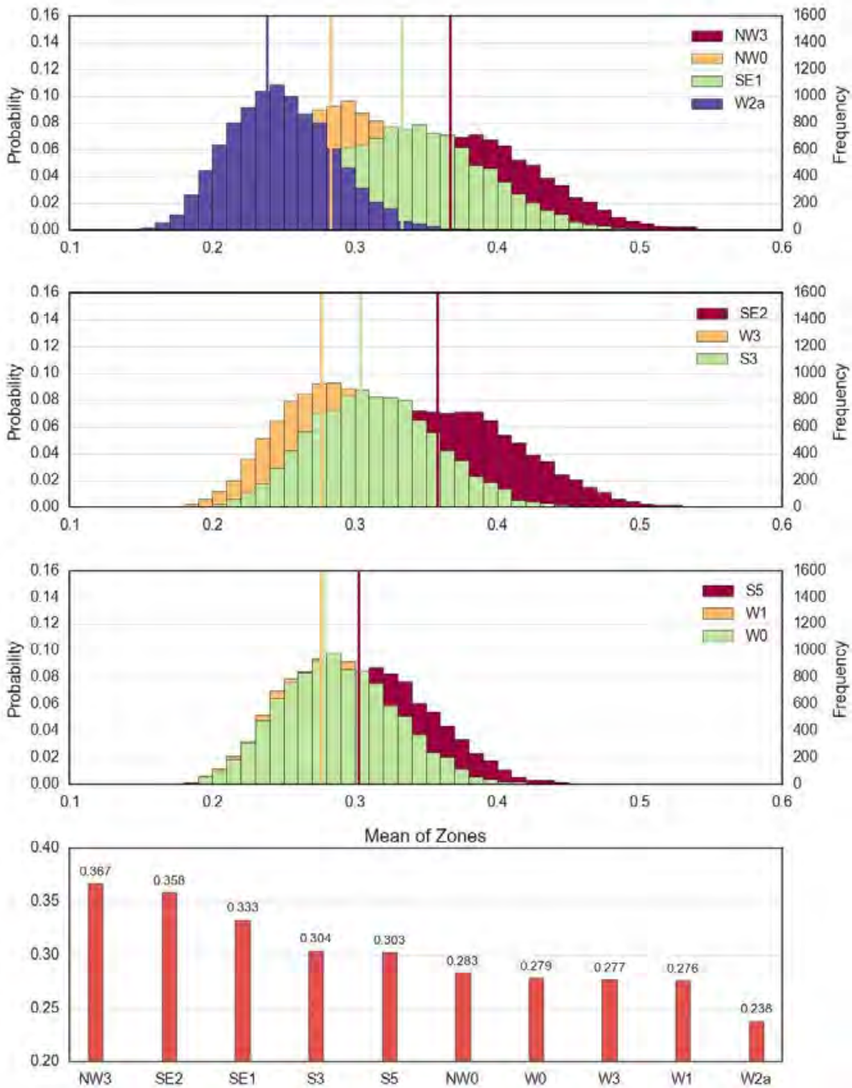



**Figure 43.** Overlay chart for the WLRI values at zone level and ranking of zones in association with 10000 runs of the Monte Carlo simulation model.

Figure 44 displays the correlation between the WLRI values that are resulted from applying the develped framework over a set of selected zones in NWDN and the total water losses for this set of zones which are based on water balance calculations . The figure shows a high correlation (around 0.80) between the two indicators for the selected zones.

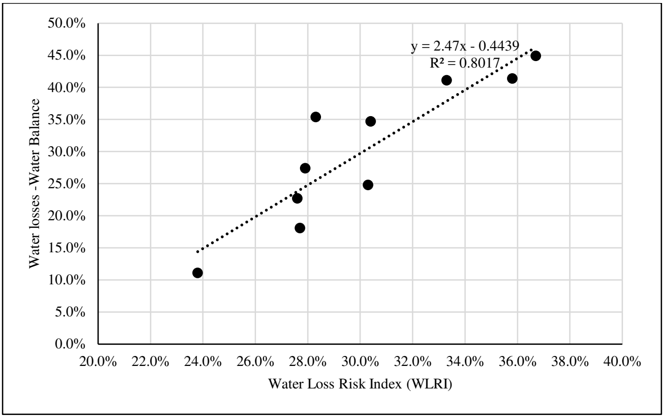



**Figure 44.** Correlation between water loss risk index (WLRI) of ten selected zones in NWDN and their total water losses from water balance calculations.

## 5.2 Discussion of outcomes of application of the simulation based multi-criteria decision making framework for evaluation of WLRI in water distribution systems

The presented FAHP methodology, which has been used to derive the priority weights of contributing factors to WLRI, offers guidelines to balance the preferences of different DMs towards the decision problem under investigation. Table 14 shows that in terms of relative importance of main categories, the physical and operational categories have attracted the largest and nearly same weights with a percentage of 40% and 39%, respectively. The environmental and social categories achieved a percentage of 11% and 9%, respectively. At basic factors level, Table 14, the pipe age basic factor in physical category was the predominant with a priority weight of 38%, followed by pipe material (19%) and pipe diameter (16%). The recognition of these factors as among the most influential ones that contribute to the performance of water pipelines is well established in several studies (Al-Barqawi & Zayed 2006; El Chanati *et al.* 2016). In the operational category, Table 14, number of breaks and pressure basic factors were nearly the predominant ones with a percentage of 29% for each of them. Average supply hours factor was in the third position in terms of its importance with a percentage of 17%. This factor is with high priority in WSNs that are operated intermittently as in the case of water supply network under investigation. In a study conducted by Agathokleous and Christodoulou (2016) to examine the vulnerability of WSNs under intermittent water supply operations, they concluded that the water loss incidents in a case study had shown an increase of 28% under intermittent practices in comparison with normal operating conditions. For the consequences factors, Table 14, number of illness that represents the impact on public health in the environmental category and the density of served population in the social category attracted the highest priority with a percentage of about 50% for each of them.

The consistency test, which is employed to judge the consistency of decisions and is required since the process of evaluation and comparison of different elements of the decision problem depends on personal understanding and feedback from diverse sources about the problem, shows that the subjective evaluations of four matrices out of five were consistent as displayed in Table 14. The results of CR values for PC1, PC2.1, PC3.1 and PC4.1 were respectively 4.49%; 8.51%; 5.64% and 9.84%. These values achieved the general rule which recommended a value of CR less than or equal to 10% for a comparison matrix to be consistent. For the matrix PC1.1, its CR was around 10% (i.e., 10.1%). In practice, when the decision problem is evaluated by experts with confidence, it is possible to use the matrix with a CR value more than 10%.

The application of FSE technique showed adequate efficiency in converting the field data of pipes into performance measures as shown as an exemplification of FSE technique in Figure 37. The reliability in its application is based to a large extent on the availability of data. The technique of visibility graph, as shown in Figure 38, was also appropriate and practical in deriving the associated weights of OVGWA operator. The employment of different techniques to derive the associated weights in OWA operator resulted in different values of aggregated measures, as shown in Table 15. This implies the need to check the reliability and robustness of outcomes of different techniques by conducting further investigations on generated data such as scenario and sensitivity analyses.

The two applied methods of aggregation of WLRI values, the OVGWA and OWALD, which have been used to generate the WLRI at zone level show different performance in terms of ranking of zones, Figure 39. The OVGWA method classified the zones in terms of their WLRI in descending order according to the following ranking (NW3, SE2, SE1, S3, S5, NW0, W1, W0, W3 and W2a). While, the ranking by OWALD method was (NW3, SE2, SE1, S5, S3, NW0, W0, W3, W1 and W2a). As it is well noted, the two methods act the same in terms of ranking the three zones which secured the highest values of WLRI (i.e. NW3, SE2 and SE1). Furthermore, they act the same in terms of ranking the zone in the sixth position (i.e. NW0) and the zone with the lowest value of WLRI (i.e. W2a). Although there are some differences in terms of ranking the zones by the two employed methods, it is possible to conclude that, the two methods are nearly acting the same. The zones that are mutually exchanged their positions are having, to a large extent, equal values of WLRI. When there was a clear distinct difference in the values of WLRI, the two methods showed the same performance in the context of ranking the zones.

The scenario analysis outputs, displayed in Figure 40 and Figure 41, showed more stable and reliable outcomes when it is applied over the OVGWA method. The robustness of the outcomes of the OVGWA method is manifested by the fact that, in most cases of applying the scenario analysis, zones have saved their rankings as in the original condition. It is evident mainly for zones with the highest values of WLRI, e.g. NW3> SE2> SE1> S3> S5 saved this pattern of ranking as in the original condition for six scenarios out of seven ones), and the zone with the lowest value of WLRI, e.g. W2a saved its position as the zone with the lowest value of WLRI in all scenario analysis conditions). In case of applying the scenario analysis over the OWALD method, the zones (NW3> SE2> SE1> S5> S3> NW0) saved this pattern of ranking in four scenarios out of seven ones. The zone with the lowest value of WLRI, e.g. W2a saved its position in all conditions associated with employing the scenario analysis. The calculations of RMSE as shown in Figure 42 confirmed the outcomes of the scenario analysis. The total value of RMSE in case of OVGWA was 0.03295, while in case of OWALD, it was 0.03564.

The final ranking of zones as a result of integration of simulation technique with an aim of acquiring better insights of zones' ranking and to examine the sensitivity of outputs to the changes in relative weights of elements of decision problem structure showed, Figure 43, this pattern of ranking in descending order (NW3> SE2> SE1> S3> S5> NW0> W0> W3> W1> W2a). The values of WLRI for five zones out of ten (i.e. NW3: 36.7%, SE2: 35.8%, SE1: 33.3%, S3: 30.4% and S5: 30.3%) were in the medium range as it is proposed that the membership functions which are used to represent the low, medium and high WLRI were respectively (0, 0, 30), (0, 30, 50) and (30, 50, 100). The other five zones attracted WLRI values in the low range (i.e. NW0: 28.3%, W0: 27.9%, W3: 27.7%, W1: 27.6% and W2a: 23.8%). By examining, for example, the characteristics of the zone with the highest value of WLRI and water losses (i.e. NW3), it was possible to conclude that most of important factors were in the region of high effect such as: the diameters of pipes in the zone were all less than 200 mm, the average age of pipes was about 40 years, the average pressure was about 100 m and the average supply hours was 4 hrs. /day. The Monte Carlo simulation analysis outcomes showed tolerable agreement in determining the ranking of zones in comparison to the original outcomes which is an indicator of reliability of applied methods. As it is well noted, there was no values within the high limits of WLRI. This can be explained by the fact that, for some basic factors (i.e. no. of breaks, quality of water, no. of illness and damage to surroundings), the lack of precise data pertaining to these factors in most cases has led to assuming values of these factors in the low effect limits. This in turn made a shift in the final values of WLRI towards the medium limit. The same case was documented by Islam *et al.* (2013). In their study to identify the WQF potential in different zones within a water supply network, they employed seventeen factors that are contributing to WQF. While the data was available for seven factors only, they assumed values for the other ten parameters less than the values of guidelines. Accordingly, this led to limited variation in WQF potential values, and the values were ranging from 30% to 50% (Islam *et al.* 2013).

There was a reasonable matching between the resulted WLRI values for the selected zones and the calculated water losses (real losses and commercial losses) for these zones in terms of ranking of these zones. These calculations as mentioned previously were based on conducting MNF analyses and estimations of different components of water balance for selected zones within

NWDS (Municipality 2016). Even though the two indicators, the WLRI and water losses, are distinct from each other and indicate different evaluations, they have the potential to indicate the criticality of zones in terms of water losses. The correlation outcomes between the previous values of the total water losses and the WLRI values of the selected zones as shown in Figure 44 indicate a high correlation ( around 0.8) between the two indicators. This indicates the reliability of the developing framework in identifying the criticality of zones in terms of water losses. Although, the real data of water losses for a set of selected zones was available based on water balance calculations, this has entailed large investments, seeking for funding, special arrangements to perform the data collection campaigns (i.e. isolation of the targeted zones and supplying water in a continuous module), and the need for large operational staff. With the importance of continuing such these activities of monitoring water losses, the developed framework offers an inexpensive and efficient tools to help water utilities in identifying the criticality of zones within WSNs. Accordingly, their incorporation in the planning policies of water utilities will yield more efficient control over water losses.

The categorization of zones within WSNs based on the potential of water losses, can help water utilities in prioritizing the application of potential strategies over zones with high priorities. In the present case, while the water utility continues the routine works of repairing the visible leaks and other maintenance works, it is possible to develop a long-term plan of applying pressure management and control, as it was selected in the previous chapters, **Section 4.1.1, Section 4.1.2, Section 4.1.3 and Section 4.1.4**, as a best strategy in reducing water losses in the examined case study, over zones with high criticality. Within a planned framework, it is possible to extend the application of this strategy over other zones. The benefits gained from this approach (i.e. reducing of water losses and energy costs) can be employed to improve the water supply services and the performance of WSNs. It is of interest to note that, the selection of potential strategies to reduce water losses is primary attached to the boundary conditions of the examined case and concerns of DMs. Accordingly, while the proposed framework is applicable to other WSNs, the potential strategy could differ from one system to another.

# 6 Conclusions[5]

This study attempted to introduce and promote the use of MCDM techniques in the field of water loss management in WSNs of the developing countries. The MCDM techniques have a great potential to improve the practical decision making processes such as in water loss management. They are able to produce compromise solutions in the existence of different multiple objectives and multiple stakeholders' interests. Moreover, they are able to structure complex decision problems and have high flexibility by giving the stakeholders a flexible approach to incorporate their own preferences. The proposed MCDM methods were tested on a real intermittent water supply system in a developing country by involving leading organizations, policy makers, and affected stakeholders to guide integrated water loss management plans. The participation of stakeholders in the decision making process and the incorporation of their preferences in the evaluation process have been a central task in this work.

The MCDM approach was first presented to support decision making in prioritizing a set of water loss management strategies that have potential in eliminating water shortage and in increasing the performance of WSNs. The practicality and efficiency of used MCDM methods in handling the decision problem were major motivations in the selection of most appropriate MCDM methods in this study. To introduce MCDM methods, which are less applied in the developing countries, in principle and in application in the context of water loss management practices, a soft MCDM method, the AHP method, was first nominated to structure the decision problem and to assist DMs in incorporating their evaluations towards the different elements of the decision problem.

The decision problem was structured by the aid of the hierarchical structure module. By this approach, it was possible to decompose the complex problem into sub problems with subsets of criteria and evaluation criteria. Furthermore, it was possible to incorporate the sustainability aspects of the decision problem. This in turn helped in producing sustainable strategies which are reliable, adequate and affordable. The involvement of DMs was considered in two phases. First, when the decision problem structure was defined to identify the dimensions of the decision problem, the evaluation criteria, alternatives and their interactions. Second, they were requested to make trade-off evaluations among criteria and evaluation criteria, and to assign the importance of different alternatives with respect to the evaluation criteria.

By applying the AHP methodology, the conclusions of all groups of DMs related to the evaluation of the decision problem elements and the most appropriate alternatives to implement the strategy were largely consistent. The results reflected the DM's interests in exploring the most effective strategies with potential to overcome the deficiencies in the water supply systems associated with the adoption of the intermittent supply scheme.

To cover functionalities that are not supported by the traditional AHP, mainly the dealing with uncertainty and incomplete information due to lack of information, incomplete knowledge, complexity of the decision problem, and to improve the accuracy and reliability of outcomes, the employment of fuzzy set theory as an extension to AHP was useful in this context. Accordingly, Fuzzy AHP was suggested in this regard. As the AHP is characterized by its clear concepts and ease of application, the Fuzzy AHP is efficient in dealing with uncertainty and incomplete information. It employs a range of values instead of fixed ones, as in case of AHP, to express DMs' uncertainty in the evaluation process. It relies on the fuzzy set theory to deal with the lack of precision in the DMs' preferences by using fuzzy numbers and associated membership functions.

[5] Parts of this chapter have been published in (Zyoud *et al.* 2016a; Zyoud *et al.* 2016b; Zyoud & Fuchs-Hanusch 2017a).

The application of two or more different MCDM methods enables a comparative analysis among the different decision elements. It allows to identify the differences in priority weights and ranking of: criteria, evaluation criteria and alternatives, and hence the reliability of the proposed decision making approach. Furthermore, it provides an opportunity to identify the most conclusive technique.

The two approaches, traditional AHP techniques and the Fuzzy AHP techniques, were appropriate in supporting group decision making. The needed mathematical operations are lower for traditional AHP techniques than for Fuzzy AHP as in some of Fuzzy AHP techniques the calculation of fuzzy synthetic extents and degrees of possibility has to be done in addition. Therefore, it can be concluded that the theoretical background of the traditional AHP is easier to understand and hence more transparent to the DMs than those of Fuzzy AHP. A central problem caused by employing some of Fuzzy AHP techniques was concerned with nulling the weights of the least preferred criteria (i.e. main criteria and evaluation criteria) and overestimating others. The employment of modified Fuzzy AHP technique was advantageous to overcome this previous shortcoming. The issue of null data is crucial as it could lead to not considering useful decision information. Accordingly, the selection of appropriate Fuzzy AHP techniques should depend on its performance of producing rational outcomes and not null data. The outcomes of modified Fuzzy AHP were in large agreement with traditional AHP techniques, the reference methods, in terms of ranking of alternatives and deviation of outputs.

The integrated methodology of Fuzzy AHP and Fuzzy TOPSIS, which was proposed in the same context of prioritizing a group of strategies as key alternatives to manage water losses showed high efficiency in handling the decision problem and in reducing the complexity of incorporating the DMs' evaluations. Its efficiency appeared to be high in case where there is a need to perform a large number of evaluations amongst the elements of the decision problem structure (i.e. evaluation the performance of alternatives against the evaluation criteria). Moreover, it showed high efficiency in reducing the complexity of computations that aimed to evaluate the importance of strategies in achieving the overall goal of reducing water losses in WSNs. By applying this methodology, it was possible to use the outcomes of Fuzzy AHP technique as inputs to Fuzzy TOPSIS. The methodology used the linguistic variables in the evaluation process and then convert them into fuzzy numbers. This activity ensured the evaluation process to be more realistic as the evaluation process has fuzziness in its nature, and is not a precise one. As in the previous applied approaches, it was possible to account for all concerns of the participating DMs. It allowed to successfully introduce the basics of integrated water loss management.

The stability and robustness of the outcomes of all applied MCDM techniques were tested by applying a sensitivity analysis. The aim was to explore the sensitivity of outputs towards the changes in inputs. This helped in deriving the robustness of the alternatives' ranking results. Furthermore, they gave an insight into the decision problem by providing an understanding of the decision problem behavior under the possible scenarios of varying of preferences.

In comparison with other MCDM techniques that have been conducted in the field of water loss management, the proposed MCDM techniques showed simplicity and practicality as they were easy to be understood by DMs in terms of implementing the required evaluations towards criteria and rating of alternatives. The different applied MCDM techniques were in large agreement in terms of ranking of pressure management (Alt. 3), establishment of district metered areas (Alt. 4) and employing of advanced techniques to fix the leaks and predict failures in WDNs (Alt. 9) as alternatives with high potential in managing of water losses in the tested case study. The previous alternatives are well known for their efficiency in managing water losses in WDNs. Moreover, the all applied MCDM techniques are nominated the public awareness and educational campaigns (Alt. 10) as the least preferred alternative.

As there were non-significant differences in terms of ranking the alternatives, mainly the most preferable and the least preferable alternatives among the different MCDM techniques, this indicates the robustness of the developed water loss management decision making framework. Furthermore, this indicates that the approach of structuring the decision problem was comprehensive and helped DMs to incorporate their evaluations in a flexible way. Accordingly, most of preferences of DMs towards these alternatives correspond with each other. Moreover, the differences in the ranking resulting from the different employed AHP techniques, different aggregation methods in Fuzzy AHP techniques and/or the integrated methodology of Fuzzy AHP and Fuzzy TOPSIS were negligible. Despite the fact that the number of participated experts in the evaluation of different decision elements of the water loss management framework was different from one technique to another, the differences were non-significant as explained previously. This additionally indicates the robustness of the developed framework.

Although, the outcomes of this analysis showed the reliability of the developed framework, the involvement of much decision makers in the evaluation process could improve much the reliability of the developed framework. This encourages further application of the developed framework over other case studies. It was possible to state that the traditional AHP techniques could be sufficient in introducing the basis of decision making and group decision making. Otherwise, the employing of Fuzzy AHP or the integrated Fuzzy AHP-Fuzzy TOPSIS techniques are required to reach greatest confidence in the outcomes and to get more reliable results as they are able to efficiently model the uncertainty in the decision making process.

The applying of previously MCDM techniques in the context of water loss management can lead to the below major conclusions:

-It is assumed that the introduced MCDM approach is useful for water utilities in terms of realizing a better understanding and assessment of components of water loss management strategies.

- It encourages group decision making approaches in principle and in practice with the aim to achieve consensus and concrete actions towards critical issues in water resources management realm.

-The incorporation of such a MCDM framework in the planning policies of water utilities in the developing countries will be useful for improving the activities that are related to water loss management.

-Moreover, it has a large potential in improving water supply services and performance of WSNs in the developing countries.

-It has the capability to work with limited, and/or lack of quantitative data, which is prevalent in most of the developing countries.

-Despite the application of different MCDM techniques, there was a large agreement in nominating the most appropriate strategies with high potential in reducing water losses (i.e. pressure management, establishment of district metered areas (DMAs) (Alt. 4) and utilizing advanced techniques (Alt. 9).

-As the final target is interested in the selection of the potential strategy, which has the adequacy to consider the interests and concerns of different stakeholders, the sustainability dimensions and the boundary conditions, the outcomes of all applied MCDM techniques were robust in this context by nominating the same strategy in most cases.

- It is possible to conclude that, the boundary and local conditions of the scrutinized case have had considerable influence on the attitudes of participants towards nominating the best alternatives. This indicates the importance of characteristics of case study in directing the preferences of DMs towards the evaluation of the decision problem.

-The nomination of pressure management as the best strategy in reducing water losses is related to its potential to ensure sufficient and efficient water supply to consumers. In the meantime, it is able to reduce unnecessary or excess pressures that contribute to unnecessarily increase of leakage from WSNs.

- The application of pressure management in the case study will be of great benefits. This is attributed to the fact that, there is insufficient definition of pressure zones in association with high differences in the altitudes which effect water pressure to reach excessive levels in the examined case study. Furthermore, the intermittent operation in association with overrated pumping facilities cause over pressure and consequently increase the rates of pipe bursts and malfunction of water meters. Accordingly, the pressure management will eliminate these deficiencies to a large extent.

-The benefits of pressure management can also extended to advantage demand and asset management.

-Some of the important strategies such as controlling of illegal use of water services and public awareness and educational campaigns attracted less attention although they have important impact on the rates of water losses, mainly in intermittent water supply systems. The less attention paid to these strategies can be related to the need for securing the customers' needs of water as a first priority.

- To improve the reliability of the outcomes, it is necessary to incorporate as much as possible the concerns of all stakeholders who have interests in this field.

-The complexity and the extent of the examined water system in addition to financial and operational constraints (this is the case in most of water supply systems in the developing countries) imply a gradual application of potential strategies in reducing water losses over selected zones with high risks of water losses.

- This gradual improvement allows to draw lessons from the practical application of potential strategies in terms of benefits and shortages. Furthermore, it allows in improving the water supply services by the investments in earned benefits to increase the efficiency of WSNs.

With respect to the last two issues, the developed Fuzzy Analytic hierarchy process-Fuzzy synthetic evaluation technique- Ordered weighted averaging operator (FAHP-FSE-OWA) hybrid framework to evaluate the WLRI at pipe and zone levels in WSNs was with adequate potential in identifying the zones according to their criticality in terms of water losses. It was based on integration of different contributing factors to water losses in WSNs. Furthermore, it has the capacity to incorporate human judgments and evaluations towards the different elements of the decision problem structure. Its major objective was devoted to support decision making in applying the best optimum strategy selected as a potential one in reducing water losses over zones that have been prioritized based on the associated WLRI values. The applicability of the proposed framework was tested by applying it over a set of selected zones in a real WSN in a developing country.

The introduced framework was based on different steps; it is initiated by identifying the most potential factors that affect water losses in WSNs. These factors are categorized according to their relevance into different categories. A group of experts was involved in the process of evaluation of relative importance of different elements of the decision problem structure. In this context, the FAHP method was used to assess the experts in reaching the final conclusion related to the importance of different elements. The FSE technique was used to establish the membership functions of basic factors. These functions are used to convert the field data into fuzzy numbers.

The resulted evaluation matrix for each set of basic factors that are belonging to each main category was multiplied by the associated weights which resulted from the FAHP method. As a result of this step, the evaluation matrix of main categories was obtainable and multiplied by the associated weights of main categories to generate the WLRI for each pipe. The OWA operator was used to aggregate the individual WLRI of pipes for each zone to generate WLRI at zone level. A scenario analysis and a Monte Carlo simulation model were used to check the robustness of the applied methods and to generate the final ranking of zones.

Generally, the outcomes of this framework were reliable as there was to a large extent an agreement in terms of ranking zones according to the associated WLRI between the traditional approach and the approach including Monte Carlo simulations. Furthermore, the ranking of zones by applying the simulation model and their ranking based on water loss calculations as an outcome of water balance estimations for the selected zones within the scrutinized case study were reasonably matched despite their distinct functions. For this framework, a group of four experts participated in the evaluation process. The inclusion of additional experts' inputs might improve the reliability further. Additionally, the inclusion of factors that have considerable contributions towards water losses in WSNs such as soil characteristics, depth of pipes, quality of installation, etc., can improve the outcomes. However, this is applicable in case of availability of required data which is mostly not the case for water utilities in developing countries. An additional issue of interest is related to the assumed thresholds for membership functions. Increasing the categories of membership functions (i.e. very low, low, medium, high, very high, etc.) might increase the ability of the applied framework to distinct the zones in a more comprehensive and detailed approach. This is favorable in case of applying the framework over a large number of zones.

In the conclusion and in spite of limitations of the proposed framework, it has the potential to assess water utilities in prioritizing the application of optimum strategies in reducing water losses over zones within WSNs that are of high priority. As a future perspective, it is applicable to integrate the developed framework with a hydraulic modelling software, geographic information systems (GIS) and other databases of water utilities to diagnose the criticality of zones within long term preventive plans. The implications of introducing such a framework in the planning policies of water utilities towards the goal of reducing the high rates of water losses are manifested in the realization of a better understanding of water loss issues, the development of well-structured and accurate databases and to encourage group decision making towards participatory and well-informed decisions in the context of water losses and water resources management. The developed framework is valid for application to other WSNs in the developing countries with similar characteristics.

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# Appendices

## Appendix A

## Survey with decision makers (DMs)

- **Research subject:** Development of a framework for strategic water loss management decisions
- **Case Study:** Nablus Water Distribution Network (NWDN)-Nablus-Palestine
- **Used tools:** Analytic hierarchy process (AHP)-multi criteria decision making techniques (MCDM)

**Background**

Water utilities in Palestine as in the most of the developing countries are struggling to reduce the gaps between available water supplies and required demands. Management of water losses in water supply networks is seen as a key to sustainable water management and in alleviating the water shortage problems. The practice of water loss management should be beyond the economic benefits. It should address environmental, social and technical aspects to provide sustainable solutions. Furthermore, it should consider the concerns and interests of different stakeholders. Accordingly, this work is seeking to develop a framework for strategic water loss management decisions and to take into account the concerns of different stakeholders in this regard. This will help in arriving at sustainable and compromise solutions. The framework is structured by the aid of a hierarchical structure module with different levels, as shown in the attached figure. The first level represents the overall objective. The second level represents the sustainability aspects. The third level represents the evaluation criteria which will be used to evaluate the performance of alternatives/strategies in the fourth level in achieving the overall objective.

Please consider the general policy of water utility of Nablus during the evaluation process which aims to maximize the reliability of water supply, improving the quality of water, increasing the rates of water saving and maintaining an affordable water supply services.

- **Requirements**

**1.)** Building the decision matrices, three levels of decision matrices are built by the researcher:

**1st level**: One decision matrix which will include the tradeoffs, in the form of pairwise comparisons, among the main criteria (economic (MC1), environmental (MC2), technical (MC3) and socio-economic (MC4)) in the second level of the hierarchy structure with respect to the overall goal in the first level-Figure A.1.

**2nd level:** Four decision matrices. Each decision matrix will include the tradeoffs, in the form of pairwise comparisons, among each set of evaluation criteria in the third level of the hierarchy structure with respect to their own main criterion in the upper level (i.e. the tradeoffs will be done among the generation of revenue (EC1-MC1), capital costs (EC2-MC1), O & M costs (EC3-MC1) and benefit period (EC4-MC1) with respect to their economic main criterion in the upper level (MC1)) and so on for other evaluation criteria-Figure A.1.

**3rd level:** Ten decision matrices. Each decision matrix will include the tradeoffs, in the form of pairwise comparisons, among the ten alternatives (Alt. 1 to Alt. 10) in the fourth level of the hierarchy structure with respect to each evaluation criterion in the upper level (i.e. the tradeoffs will be done among the ten alternatives (Alt. 1 to Alt. 10) with respect to generation of revenue (EC1-MC1) in the upper level). The same will be done for the ten alternatives with respect to each evaluation criterion- Figure A.1.

**2.)** Used scale, the DM has to use a verbal scale (Saaty scale) which will be converted into numerical values in evaluating the preference of one element over another at a time (i.e. comparing the performance of one alternative over another towards a specific evaluation criterion). The scale is explained in Table A.1 below:

**Table A.1**: Saaty scale for pairwise comparisons in AHP

| Judgment term | Saaty ($a_{ij}$) |
|---|---|
| Absolute preference (element *i* over element *j*) | 9 |
| Very strong preference (*i* over *j*) | 7 |
| Strong preference (*i* over *j*) | 5 |
| Weak preference (*i* over *j*) | 3 |
| Indifference as regards *i* and *j* | 1 |
| Weak preference (*j* over *i*) | 1/3 |
| Strong preference (*j* over *i*) | 1/5 |
| Very strong preference (*j* over *i*) | 1/7 |
| Absolute preference (*j* over *i*) | 1/9 |
| When compromise is needed-intermediate values | 2, 4, 6, 8.....1/2, 1/4, 1/6, 1/8 |

**3.)** The DM has to try to ask two questions for each entry in the evaluation matrix, e.g. in case the DM wants to express his/her preferences among two alternatives with respect to a specific criterion, the two questions are:

- Which is more important with respect to the criterion?
- How strongly?

- **Example**

Please refer to the following example which clarifies the evaluation procedure required to make tradeoffs among the main criteria (economic (MC1), environmental (MC2), technical (MC3) and socio-economic (MC4)) in the second level of the hierarchy structure with respect to the overall goal in the upper level-Figure 1.

- If the DM found that the economic criterion (MC1) is with absolute preference to the overall objective compared to the environmental criterion (MC2), the entry will be [9].
- If the DM found that the economic criterion (MC1) is with strong preference to the overall objective compared to the technical criterion (MC3), the entry will be [5].
- If the DM found that the socio-economic (MC4) criterion is with very strong preference to the overall objective compared to the economic criterion (MC1), the entry will be [7] on the side of socio-economic criterion and [1/7] for the economic criterion which will appear in the decision matrix.
- If the DM found that the environmental criterion (MC2) is with weak preference to the overall objective compared to the technical criterion (MC3), the entry will be [3].
- If the DM found that the environmental criterion (MC2) is with strong preference to the overall objective compared to the socio-economic criterion (MC4), the entry will be [5].
- If the DM found that the technical criterion (MC3) is with absolute preference to the overall objective compared to the socio-economic criterion (MC4), the entry will be [9].

**Overall objective**

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ☒ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| Economic (MC1) | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Environmental (MC2) |
| | ☐ | ☐ | ☐ | ☐ | ☒ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| Economic (MC1) | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Technical (MC3) |
| | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☒ | ☐ | ☐ | |
| Economic (MC1) | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Socio-economic (MC4) |
| | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☒ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| Environmental (MC2) | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Technical (MC3) |
| | ☐ | ☐ | ☐ | ☐ | ☒ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| Environmental (MC2) | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Socio-economic (MC4) |
| | ☒ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| Technical (MC3) | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Socio-economic (MC4) |

- The final filled decision matrix will be as follows :

| Overall Objective | Economic (MC1) | Environmental (MC2) | Technical (MC3) | Socio-economic (MC4) |
|---|---|---|---|---|
| Economic (MC1) | 1 | 9 | 5 | 1/7 |
| Environmental (MC2) | 1/9 | 1 | 3 | 5 |
| Technical (MC3) | 1/5 | 1/3 | 1 | 9 |
| Socio-economic (MC4) | 7 | 1/5 | 1/9 | 1 |

- For the diagonal, all values equal 1 as the comparison between the elements themselves.
- Under the diagonal, the values will be reciprocal to the values above the diagonal (no need to fill under the diagonal in the evaluation matrix, it is the responsibility of the researcher to complete these entries).

- Please refer to the following items before proceeding with the evaluation process:

  -Figure A.1, which illustrates the hierarchy structure of the decision problem,
  -Table A.2, which displays the set of evaluation criteria with more details.
  -Table A.3, which displays the set of alternatives with more details.

- Please try to express your preferences as a DM in the following decision matrices.

**Level 1:** Please make pairwise comparisons between each two elements at a time (two main criteria) with respect to the overall goal by using the scale in Table A.1. No need to fill in the diagonal and under the diagonal.

| Overall Objective | Economic (MC1) | Environmental (MC2) | Technical (MC3) | Socio-economic (MC4) |
|---|---|---|---|---|
| Economic (MC1) | 1 | | | |
| Environmental (MC2) | | 1 | | |
| Technical (MC3) | | | 1 | |
| Socio-economic (MC4) | | | | 1 |

**Level 2:** Please make pairwise comparisons between each two elements at a time (two evaluation criteria) with respect to their own criterion by using the scale in Table A.1. No need to fill in the diagonal and under the diagonal.

| Economic (MC1) | Generation of revenue (EC1-MC1) | Capital costs (EC2-MC1) | O & M costs (EC3-MC1) | Benefit period (EC4-MC1) |
|---|---|---|---|---|
| Generation of revenue (EC1-MC1) | 1 | | | |
| Capital costs (EC2-MC1) | | 1 | | |
| O & M costs (EC3-MC1) | | | 1 | |
| Benefit period (EC4-MC1) | | | | 1 |

| Environmental (MC2) | Water preservation (EC5-MC2) | Saving of energy (EC6-MC2) |
|---|---|---|
| Water preservation (EC5-MC2) | 1 | |
| Saving of energy (EC6-MC2) | | 1 |

| Technical (MC3) | Supply reliability (EC7-MC3) | Flexibility (EC8-MC3) |
|---|---|---|
| Supply reliability (EC7-MC3) | 1 | |
| Flexibility (EC8-MC3) | | 1 |

| Socio-economic (MC4) | Affordability (EC9-MC4) | Water quality (EC10-MC4) |
|---|---|---|
| Affordability (EC9-MC4) | 1 | |
| Water quality (EC10-MC4) | | 1 |

**Level 3:** Please make pairwise comparisons between each two elements at a time (two alternatives) with respect to each evaluation criterion by using the scale in Table A.1. No need to fill in the diagonal and under the diagonal.

| Generation of revenue (EC1-MC1) | Active leakage control (Alt. 1) | Passive leakage control (Alt. 2) | Pressure control (Alt. 3) | Establishment of DMAs (Alt. 4) | Asset management (Alt. 5) | Replacement of water meters (Alt. 6) | Improving repairs (Alt. 7) | Control of illegal use (Alt. 8) | Utilizing advanced techniques (Alt. 9) | Public awareness (Alt. 10) |
|---|---|---|---|---|---|---|---|---|---|---|
| Active leakage control (Alt. 1) | 1 | | | | | | | | | |
| Passive leakage control (Alt. 2) | | 1 | | | | | | | | |
| Pressure control (Alt. 3) | | | 1 | | | | | | | |
| Establishment of DMAs (Alt. 4) | | | | 1 | | | | | | |
| Asset management (Alt. 5) | | | | | 1 | | | | | |
| Replacement of water meters (Alt. 6) | | | | | | 1 | | | | |
| Improving repairs (Alt. 7) | | | | | | | 1 | | | |
| Control of illegal use (Alt. 8) | | | | | | | | 1 | | |
| Utilizing advanced techniques (Alt. 9) | | | | | | | | | 1 | |
| Public awareness (Alt. 10) | | | | | | | | | | 1 |

| Capital costs (EC2-MC1) | Active leakage control (Alt. 1) | Passive leakage control (Alt. 2) | Pressure control (Alt. 3) | Establishment of DMAs (Alt. 4) | Asset management (Alt. 5) | Replacement of water meters (Alt. 6) | Improving repairs (Alt. 7) | Control of illegal use (Alt. 8) | Utilizing advanced techniques (Alt. 9) | Public awareness (Alt. 10) |
|---|---|---|---|---|---|---|---|---|---|---|
| Active leakage control (Alt. 1) | 1 | | | | | | | | | |
| Passive leakage control (Alt. 2) | | 1 | | | | | | | | |
| Pressure control (Alt. 3) | | | 1 | | | | | | | |
| Establishment of DMAs (Alt. 4) | | | | 1 | | | | | | |
| Asset management (Alt. 5) | | | | | 1 | | | | | |
| Replacement of water meters (Alt. 6) | | | | | | 1 | | | | |
| Improving repairs (Alt. 7) | | | | | | | 1 | | | |
| Control of illegal use (Alt. 8) | | | | | | | | 1 | | |
| Utilizing advanced techniques (Alt. 9) | | | | | | | | | 1 | |
| Public awareness (Alt. 10) | | | | | | | | | | 1 |

| O & M costs (EC3-MC1) | Active leakage control (Alt. 1) | Passive leakage control (Alt. 2) | Pressure control (Alt. 3) | Establishment of DMAs (Alt. 4) | Asset management (Alt. 5) | Replacement of water meters (Alt. 6) | Improving repairs (Alt. 7) | Control of illegal use (Alt. 8) | Utilizing advanced techniques (Alt. 9) | Public awareness (Alt. 10) |
|---|---|---|---|---|---|---|---|---|---|---|
| Active leakage control (Alt. 1) | 1 | | | | | | | | | |
| Passive leakage control (Alt. 2) | | 1 | | | | | | | | |
| Pressure control (Alt. 3) | | | 1 | | | | | | | |
| Establishment of DMAs (Alt. 4) | | | | 1 | | | | | | |
| Asset management (Alt. 5) | | | | | 1 | | | | | |
| Replacement of water meters (Alt. 6) | | | | | | 1 | | | | |
| Improving repairs (Alt. 7) | | | | | | | 1 | | | |
| Control of illegal use (Alt. 8) | | | | | | | | 1 | | |
| Utilizing advanced techniques (Alt. 9) | | | | | | | | | 1 | |
| Public awareness (Alt. 10) | | | | | | | | | | 1 |

| Benefit period (EC4-MC1) | Active leakage control (Alt. 1) | Passive leakage control (Alt. 2) | Pressure control (Alt. 3) | Establishment of DMAs (Alt. 4) | Asset management (Alt. 5) | Replacement of water meters (Alt. 6) | Improving repairs (Alt. 7) | Control of illegal use (Alt. 8) | Utilizing advanced techniques (Alt. 9) | Public awareness (Alt. 10) |
|---|---|---|---|---|---|---|---|---|---|---|
| Active leakage control (Alt. 1) | 1 | | | | | | | | | |
| Passive leakage control (Alt. 2) | | 1 | | | | | | | | |
| Pressure control (Alt. 3) | | | 1 | | | | | | | |
| Establishment of DMAs (Alt. 4) | | | | 1 | | | | | | |
| Asset management (Alt. 5) | | | | | 1 | | | | | |
| Replacement of water meters (Alt. 6) | | | | | | 1 | | | | |
| Improving repairs (Alt. 7) | | | | | | | 1 | | | |
| Control of illegal use (Alt. 8) | | | | | | | | 1 | | |
| Utilizing advanced techniques (Alt. 9) | | | | | | | | | 1 | |
| Public awareness (Alt. 10) | | | | | | | | | | 1 |

| Water preservation (EC5-MC2) | Active leakage control (Alt. 1) | Passive leakage control (Alt. 2) | Pressure control (Alt. 3) | Establishment of DMAs (Alt. 4) | Asset management (Alt. 5) | Replacement of water meters (Alt. 6) | Improving repairs (Alt. 7) | Control of illegal use (Alt. 8) | Utilizing advanced techniques (Alt. 9) | Public awareness (Alt. 10) |
|---|---|---|---|---|---|---|---|---|---|---|
| Active leakage control (Alt. 1) | 1 | | | | | | | | | |
| Passive leakage control (Alt. 2) | | 1 | | | | | | | | |
| Pressure control (Alt. 3) | | | 1 | | | | | | | |
| Establishment of DMAs (Alt. 4) | | | | 1 | | | | | | |
| Asset management (Alt. 5) | | | | | 1 | | | | | |
| Replacement of water meters (Alt. 6) | | | | | | 1 | | | | |
| Improving repairs (Alt. 7) | | | | | | | 1 | | | |
| Control of illegal use (Alt. 8) | | | | | | | | 1 | | |
| Utilizing advanced techniques (Alt. 9) | | | | | | | | | 1 | |
| Public awareness (Alt. 10) | | | | | | | | | | 1 |

| Saving of energy (EC6-MC2) | Active leakage control (Alt. 1) | Passive leakage control (Alt. 2) | Pressure control (Alt. 3) | Establishment of DMAs (Alt. 4) | Asset management (Alt. 5) | Replacement of water meters (Alt. 6) | Improving repairs (Alt. 7) | Control of illegal use (Alt. 8) | Utilizing advanced techniques (Alt. 9) | Public awareness (Alt. 10) |
|---|---|---|---|---|---|---|---|---|---|---|
| Active leakage control (Alt. 1) | 1 | | | | | | | | | |
| Passive leakage control (Alt. 2) | | 1 | | | | | | | | |
| Pressure control (Alt. 3) | | | 1 | | | | | | | |
| Establishment of DMAs (Alt. 4) | | | | 1 | | | | | | |
| Asset management (Alt. 5) | | | | | 1 | | | | | |
| Replacement of water meters (Alt. 6) | | | | | | 1 | | | | |
| Improving repairs (Alt. 7) | | | | | | | 1 | | | |
| Control of illegal use (Alt. 8) | | | | | | | | 1 | | |
| Utilizing advanced techniques (Alt. 9) | | | | | | | | | 1 | |
| Public awareness (Alt. 10) | | | | | | | | | | 1 |

| Supply reliability (EC7-MC3) | Active leakage control (Alt. 1) | Passive leakage control (Alt. 2) | Pressure control (Alt. 3) | Establishment of DMAs (Alt. 4) | Asset management (Alt. 5) | Replacement of water meters (Alt. 6) | Improving repairs (Alt. 7) | Control of illegal use (Alt. 8) | Utilizing advanced techniques (Alt. 9) | Public awareness (Alt. 10) |
|---|---|---|---|---|---|---|---|---|---|---|
| Active leakage control (Alt. 1) | 1 | | | | | | | | | |
| Passive leakage control (Alt. 2) | | 1 | | | | | | | | |
| Pressure control (Alt. 3) | | | 1 | | | | | | | |
| Establishment of DMAs (Alt. 4) | | | | 1 | | | | | | |
| Asset management (Alt. 5) | | | | | 1 | | | | | |
| Replacement of water meters (Alt. 6) | | | | | | 1 | | | | |
| Improving repairs (Alt. 7) | | | | | | | 1 | | | |
| Control of illegal use (Alt. 8) | | | | | | | | 1 | | |
| Utilizing advanced techniques (Alt. 9) | | | | | | | | | 1 | |
| Public awareness (Alt. 10) | | | | | | | | | | 1 |

| Flexibility (EC8-MC3) | Active leakage control (Alt. 1) | Passive leakage control (Alt. 2) | Pressure control (Alt. 3) | Establishment of DMAs (Alt. 4) | Asset management (Alt. 5) | Replacement of water meters (Alt. 6) | Improving repairs (Alt. 7) | Control of illegal use (Alt. 8) | Utilizing advanced techniques (Alt. 9) | Public awareness (Alt. 10) |
|---|---|---|---|---|---|---|---|---|---|---|
| Active leakage control (Alt. 1) | 1 | | | | | | | | | |
| Passive leakage control (Alt. 2) | | 1 | | | | | | | | |
| Pressure control (Alt. 3) | | | 1 | | | | | | | |
| Establishment of DMAs (Alt. 4) | | | | 1 | | | | | | |
| Asset management (Alt. 5) | | | | | 1 | | | | | |
| Replacement of water meters (Alt. 6) | | | | | | 1 | | | | |
| Improving repairs (Alt. 7) | | | | | | | 1 | | | |
| Control of illegal use (Alt. 8) | | | | | | | | 1 | | |
| Utilizing advanced techniques (Alt. 9) | | | | | | | | | 1 | |
| Public awareness (Alt. 10) | | | | | | | | | | 1 |

| Affordability (EC9-MC4) | Active leakage control (Alt. 1) | Passive leakage control (Alt. 2) | Pressure control (Alt. 3) | Establishment of DMAs (Alt. 4) | Asset management (Alt. 5) | Replacement of water meters (Alt. 6) | Improving repairs (Alt. 7) | Control of illegal use (Alt. 8) | Utilizing advanced techniques (Alt. 9) | Public awareness (Alt. 10) |
|---|---|---|---|---|---|---|---|---|---|---|
| Active leakage control (Alt. 1) | 1 | | | | | | | | | |
| Passive leakage control (Alt. 2) | | 1 | | | | | | | | |
| Pressure control (Alt. 3) | | | 1 | | | | | | | |
| Establishment of DMAs (Alt. 4) | | | | 1 | | | | | | |
| Asset management (Alt. 5) | | | | | 1 | | | | | |
| Replacement of water meters (Alt. 6) | | | | | | 1 | | | | |
| Improving repairs (Alt. 7) | | | | | | | 1 | | | |
| Control of illegal use (Alt. 8) | | | | | | | | 1 | | |
| Utilizing advanced techniques (Alt. 9) | | | | | | | | | 1 | |
| Public awareness (Alt. 10) | | | | | | | | | | 1 |

| Water quality (EC10-MC4) | Active leakage control (Alt. 1) | Passive leakage control (Alt. 2) | Pressure control (Alt. 3) | Establishment of DMAs (Alt. 4) | Asset management (Alt. 5) | Replacement of water meters (Alt. 6) | Improving repairs (Alt. 7) | Control of illegal use (Alt. 8) | Utilizing advanced techniques (Alt. 9) | Public awareness (Alt. 10) |
|---|---|---|---|---|---|---|---|---|---|---|
| Active leakage control (Alt. 1) | 1 | | | | | | | | | |
| Passive leakage control (Alt. 2) | | 1 | | | | | | | | |
| Pressure control (Alt. 3) | | | 1 | | | | | | | |
| Establishment of DMAs (Alt. 4) | | | | 1 | | | | | | |
| Asset management (Alt. 5) | | | | | 1 | | | | | |
| Replacement of water meters (Alt. 6) | | | | | | 1 | | | | |
| Improving repairs (Alt. 7) | | | | | | | 1 | | | |
| Control of illegal use (Alt. 8) | | | | | | | | 1 | | |
| Utilizing advanced techniques (Alt. 9) | | | | | | | | | 1 | |
| Public awareness (Alt. 10) | | | | | | | | | | 1 |

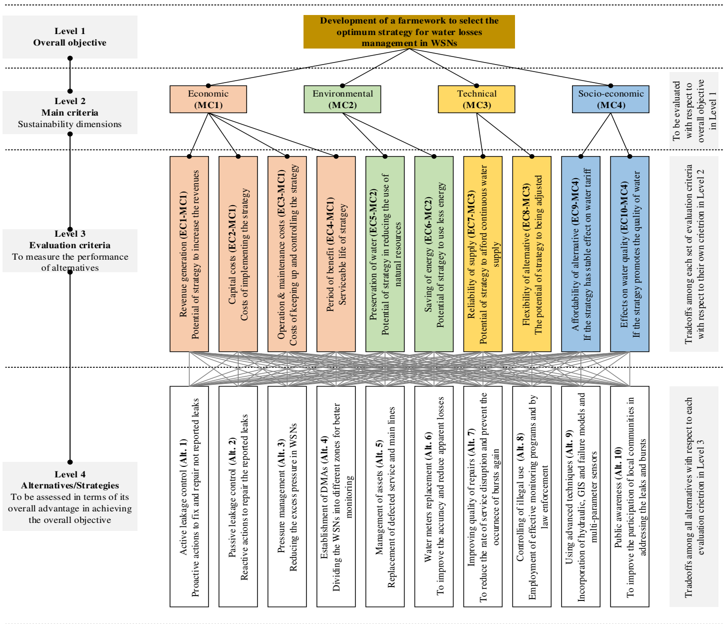


**Figure A.1.** Illustration of water loss management hierarchical structure framework.

**Table A.2.** Proposed evaluation criteria which will be used to measure the performance of alternatives in achieving the overall objective

| Code | Evaluation Criteria (EC) | Objective Class-Category | Maximize or Minimize | Explanations |
|---|---|---|---|---|
| EC1-MC1 | Generation of revenue | Economic | Maximize | If the alternative contributes to produce and increase the revenue. (It is most preferable in case it has more potential to increase the revenue) |
| EC2-MC1 | Capital costs | Economic | Minimize | Associated costs to implement the alternative. (It is most preferable in case it has lower figure of costs) |
| EC3-MC1 | Operation & Maintenance costs | Economic | Minimize | Costs associated with control and upkeep of the alternative. (It is most preferable in case it needs low costs) |
| EC4-MC1 | Benefit period | Economic | Maximize | Measuring the useful life span of the alternative. (It is most preferable in case the alternative has longer life cycle) |
| EC5-MC2 | Water preservation & reduction of waste | Environmental | Maximize | If the alternative has the ability to maximize water savings and minimize the pressure on natural resources through reducing water losses. (It is most preferable in case its output of saving water is high) |
| EC6-MC2 | Energy saved | Environmental | Maximize | If the alternative has the ability to minimize the energy consumption and greenhouse gas emissions. (It is most preferable in case its output of saving energy is high) |
| EC7-MC3 | Supply reliability | Technical | Maximize | If the alternative has the ability to save most continuous service and minimize supply interruptions. (It is most preferable in case the proposed alternative has lower level of leaks frequencies) |
| EC8-MC3 | Flexibility | Technical | Maximize | If the alternative has the capability of being adjusted to meet varied needs and uncertainties. (It is most preferable in case the proposed option has high flexibility) |
| EC9-MC4 | Affordability | Socio-economic | Maximize | Measuring the impact of alternative on level of water tariff. (It is most preferable in case the proposed alternative has a stable effect on tariff) |
| EC10-MC4 | Water quality | Socio-economic | Maximize | Measuring the ability of alternative to improve water quality. (It is most preferable in case the proposed alternative has a strong potential to improve water quality) |

**Table A.3.** Proposed strategy alternatives which may contribute to the achievement of the objectives

| Code | Alternative | Explanations |
|---|---|---|
| Alt. 1 | Active leakage control | Which includes taking actions in the distribution system to identify and repair leaks that have not been reported (proactive control) |
| Alt. 2 | Passive leakage control | Repairing reported or evident leaks only, water loss is tackled when leakage is visible, or the problem is reported form the public (reactive control) |
| Alt. 3 | Operational pressure control & management | Managing system pressures to the optimum levels of service ensuring sufficient and efficient supply to customers, while reducing unnecessary or excess pressures, which reduces the leakage, extends useful life of infrastructure, and reduces operation and maintenance costs, using PRVs |
| Alt. 4 | Establishing district metering areas (DMAs) | Useful for improving the management of the network, monitoring the input and the output discharges, DMAs have more homogenous characteristics, and can be used to determine leakage within an area that can be isolated |
| Alt. 5 | Asset management for service lines & selective mains | Replacement of affected service lines and mains |
| Alt. 6 | Replacement of water meters | To eliminate water meter inaccuracy, may include installation of automatic water meters |
| Alt. 7 | Improving quality level of repairs & minimizing the required time of repairing | To prevent the occurrence of bursts again, and to minimize the volumes of lost water and to minimize the adverse effects of disruption of the service |
| Alt. 8 | Control of illegal use of water service | To eliminate the illegal use of water through public awareness campaigns, and effective monitoring |
| Alt. 9 | Utilizing advanced techniques to fix & predict the leakage | Useful to fix the location of leaks and to predict failures, include concrete database, hydraulic and GIS models, predicting failure models, installing pressure sensors, noise and flow sensors to monitor the variations in the network |
| Alt. 10 | Public awareness & educational campaigns | Useful to accelerate the process of fixing and repairing visible leakage and bursts and promotes the conservation measures |

## Appendix B

## Survey with decision makers (DMs)

- **Research subject:** Development of a framework for strategic water loss management decisions
- **Case Study:** Nablus Water Distribution Network (NWDN)-Nablus-Palestine
- **Used tools:** An integrated methodology of Fuzzy Analytic hierarchy process (Fuzzy AHP) and Fuzzy Technique for order of preference by similarity to ideal solution (Fuzzy TOPSIS)-multi criteria decision making techniques (MCDM)

**Background**

Water utilities in Palestine as in the most of the developing countries are struggling to reduce the gaps between available water supplies and required demands. Management of water losses in water supply networks is seen as a key to sustainable water management and in alleviating the water shortage problems. The practice of water loss management should be beyond the economic benefits. It should address environmental, social and technical aspects to provide sustainable solutions. Furthermore, it should consider the concerns and interests of different stakeholders. Accordingly, this work is seeking to develop a framework for strategic water loss management decisions and to take into account the concerns of different stakeholders in this regard. This will help in arriving at sustainable and compromise solutions. The framework is structured by the aid of a hierarchical structure module with different levels, as shown in the attached figure. The first level represents the overall objective. The second level represents the sustainability aspects. The third level represents the evaluation criteria which will be used to evaluate the performance of alternatives/strategies in the fourth level in achieving the overall objective.

Please consider the general policy of water utility of Nablus during the evaluation process which aims to maximize the reliability of water supply, improving the quality of water, increasing the rates of water saving and maintaining an affordable water supply services.

- **Requirements**

➢ **Requirements of Fuzzy AHP technique**

**1.)** Building the decision matrices, two levels of decision matrices are built by the researcher:

**1st level**: One decision matrix which will include the tradeoffs, in the form of pairwise comparisons, among the main criteria (economic (MC1), environmental (MC2), technical (MC3) and socio-economic (MC4)) in the second level of the hierarchy structure with respect to the overall goal in the first level-Figure B.1.

**2nd level:** Four decision matrices. Each decision matrix will include the tradeoffs, in the form of pairwise comparisons, among each set of evaluation criteria in the third level of the hierarchy structure with respect to their own main criterion in the upper level (i.e. the tradeoffs will be done among the generation of revenue (EC1-MC1), capital costs (EC2-MC1), O & M costs (EC3-MC1) and benefit period (EC4-MC1) with respect to their economic main criterion in the upper level (MC1)) and so on for other evaluation criteria-Figure B.1.

**2.)** Used scale, the DM has to use linguistic terms, which will be converted into triangular fuzzy numbers (TFNs), in evaluating the preference of one element over another at a time (i.e. comparing the performance of one alternative over another towards a specific evaluation criterion). The scale is explained in Table B.1 below:

**Table B.1.** Definition of linguistic evaluation (Weight importance of criteria and evaluation criteria)

| Linguistic variables | Code | Explanation | Positive TFN | Reciprocal TFN |
|---|---|---|---|---|
| Equal Importance | EI | Two criteria equally contribute | (1, 1, 1) | (1, 1, 1) |
| Moderate Importance | MI | Experience and judgment moderately favor one criterion over another | (1, 3, 5) | (1/5, 1/3, 1) |
| Strong Importance | SI | Experience and judgment strongly favor one criterion over another | (3, 5, 7) | (1/7, 1/5, 1/3) |
| Very Strong Importance | VSI | A criterion is favored very strongly over another | (5, 7, 9) | (1/9, 1/7, 1/5) |
| Extreme importance | EXI | A criterion is extremely favored over another | (7, 9, 9) | (1/9, 1/9, 1/7) |

**3.)** The DM has to try to ask two questions for each entry in the evaluation matrix, e.g. in case the DM wants to express his/her preferences among two alternatives with respect to a specific criterion, the two questions are:

➢ Which is more important with respect to the criterion?
➢ How strongly?

- **Example**

Please refer to the following example which clarifies the evaluation procedure required to make tradeoffs among the main criteria (economic (MC1), environmental (MC2), technical (MC3) and socio-economic (MC4)) in the second level of the hierarchy structure with respect to the overall goal in the upper level-Figure B.1.

- If the DM found that the economic criterion (MC1) is with extreme importance to the overall objective compared to the environmental criterion (MC2), the entry will be [EXI].
- If the DM found that the economic criterion (MC1) is with strong importance to the overall objective compared to the technical criterion (MC3), the entry will be [SI].
- If the DM found that the socio-economic (MC4) criterion is with very strong importance to the overall objective compared to the economic criterion (MC1), the entry will be [VSI] on the side of socio-economic criterion and [ (VSI) ] for the economic criterion which will appear in the decision matrix. The term between parentheses indicates reciprocal of the original term.
- If the DM found that the environmental criterion (MC2) is with moderate importance to the overall objective compared to the technical criterion (MC3), the entry will be [MI].
- If the DM found that the environmental criterion (MC2) is with strong importance to the overall objective compared to the socio-economic criterion (MC4), the entry will be [SI].
- If the DM found that the technical criterion (MC3) is with extreme importance to the overall objective compared to the socio-economic criterion (MC4), the entry will be [EXI].

- The final filled decision matrix will be as follows :

| Overall Objective | Economic (MC1) | Environmental (MC2) | Technical (MC3) | Socio-economic (MC4) |
|---|---|---|---|---|
| Economic (MC1) | EI | EXI | SI | (VSI) |
| Environmental (MC2) | | EI | MI | SI |
| Technical (MC3) | | | EI | EXI |
| Socio-economic (MC4) | | | | EI |

- For the diagonal, all values are EI as the comparison between the elements themselves.
- Under the diagonal, the values will be reciprocal to the values above the diagonal (no need to fill under the diagonal in the evaluation matrix, it is the responsibility of the researcher to complete these entries).

- Please refer to the following items before proceeding with the evaluation process:
  -Figure B.1, which illustrates the hierarchy structure of the decision problem,
  -Table B.3, which displays the set of evaluation criteria with more details.
  -Table B.4, which displays the set of alternatives with more details.

- Please try to express your preferences as a DM in the following decision matrices.

**Level 1:** Please make pairwise comparisons between each two elements at a time (two main criteria) with respect to the overall goal by using the linguistic terms in Table B.1. No need to fill in the diagonal and under the diagonal.

| Overall Objective | Economic (MC1) | Environmental (MC2) | Technical (MC3) | Socio-economic (MC4) |
|---|---|---|---|---|
| Economic (MC1) | EI | | | |
| Environmental (MC2) | | EI | | |
| Technical (MC3) | | | EI | |
| Socio-economic (MC4) | | | | EI |

**Level 2:** Please make pairwise comparisons between each two elements at a time (two evaluation criteria) with respect to their own criterion by using the linguistic terms in Table B.1. No need to fill in the diagonal and under the diagonal.

| Economic (MC1) | Generation of revenue (EC1-MC1) | Capital costs (EC2-MC1) | O & M costs (EC3-MC1) | Benefit period (EC4-MC1) |
|---|---|---|---|---|
| Generation of revenue (EC1-MC1) | EI | | | |
| Capital costs (EC2-MC1) | | EI | | |
| O & M costs (EC3-MC1) | | | EI | |
| Benefit period (EC4-MC1) | | | | EI |

| Environmental (MC2) | Water preservation (EC5-MC2) | Saving of energy (EC6-MC2) |
|---|---|---|
| Water preservation (EC5-MC2) | EI | |
| Saving of energy (EC6-MC2) | | EI |

| Technical (MC3) | Supply reliability (EC7-MC3) | Flexibility (EC8-MC3) |
|---|---|---|
| Supply reliability (EC7-MC3) | EI | |
| Flexibility (EC8-MC3) | | EI |

| Socio-economic (MC4) | Affordability (EC9-MC4) | Water quality (EC10-MC4) |
|---|---|---|
| Affordability (EC9-MC4) | EI | |
| Water quality (EC10-MC4) | | EI |

➢ **Requirements of Fuzzy TOPSIS technique**

**1.)** Building the evaluation matrix:

**3rd level**: One evaluation matrix which will include in each line the performance of each alternative towards the set of evaluation criteria.

**2.)** Used scale, the DM has to use linguistic terms, which will be converted into triangular fuzzy numbers (TFNs), in evaluating the performance of an alternative towards each evaluation criterion at a time. The scale is explained in Table B.2 below:

**Table B.2.** Definition of linguistic evaluation (Ratings for alternatives with respect to evaluation criteria)

| Linguistic variables | Code | Positive TFN |
|---|---|---|
| Very Poor | VP | (1, 1, 1) |
| Poor | P | (1, 3, 5) |
| Fair | F | (3, 5, 7) |
| Good | G | (5, 7, 9) |
| Very Good | VG | (7, 9, 9) |

- **Example**

Please refer to the following example which clarifies the evaluation procedure required to rate the performance of active leakage control alternative (Alt. 1) towards a set of evaluation criteria.

- If the DM found that Alt.1 is very poor in generation of revenues (EC1-MC1), the entry will be [VP].
- If the DM found that Alt.1 is fair in capital costs (EC2-MC1), the entry will be [F].
- If the DM found that Alt.1 is poor in saving of energy (EC6-MC2), the entry will be [P].

| | Generation of revenue (EC1-MC1) | Capital costs (EC2-MC1) | O & M costs (EC3-MC1) | Benefit period (EC4-MC1) | Water preservation (EC5-MC2) | Saving of energy (EC6-MC2) | Reliability of supply (EC7-MC3) | Flexibility (EC8-MC3) | Affordability (EC9-MC4) | Water quality (EC10-MC4) |
|---|---|---|---|---|---|---|---|---|---|---|
| Active leakage control (Alt. 1) | VP | F | | | | P | | | | |

- Please try, as a DM, to rate the performance of each alternative towards each evaluation criterion by using the linguistic terms in Table B.2.

| | Generation of revenue (EC1-MC1) | Capital costs (EC2-MC1) | O & M costs (EC3-MC1) | Benefit period (EC4-MC1) | Water preservation (EC5-MC2) | Saving of energy (EC6-MC2) | Reliability of supply (EC7-MC3) | Flexibility (EC8-MC3) | Affordability (EC9-MC4) | Water quality (EC10-MC4) |
|---|---|---|---|---|---|---|---|---|---|---|
| Active leakage control (Alt. 1) | | | | | | | | | | |
| Passive leakage control (Alt. 2) | | | | | | | | | | |
| Pressure control (Alt. 3) | | | | | | | | | | |
| Establishment of DMAs (Alt. 4) | | | | | | | | | | |
| Asset management (Alt. 5) | | | | | | | | | | |
| Replacement of water meters (Alt. 6) | | | | | | | | | | |
| Improving repairs (Alt. 7) | | | | | | | | | | |
| Control of illegal use (Alt. 8) | | | | | | | | | | |
| Utilizing advanced techniques (Alt. 9) | | | | | | | | | | |
| Public awareness (Alt. 10) | | | | | | | | | | |

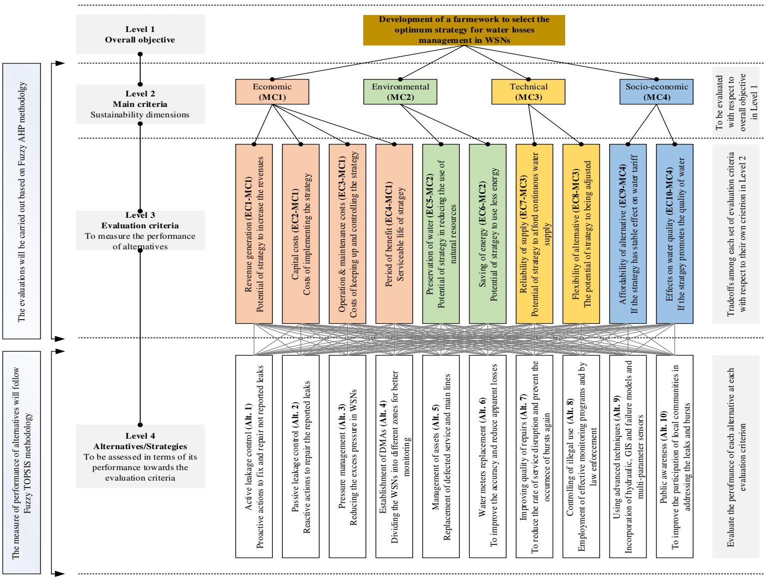


**Figure B.1.** Illustration of water loss management hierarchical structure framework.

**Table B.2.** Proposed evaluation criteria which will be used to measure the performance of alternatives in achieving the overall objective

| Code | Evaluation Criteria (EC) | Objective Class-Category | Maximize or Minimize | Explanations |
|---|---|---|---|---|
| EC1-MC1 | Generation of revenue | Economic | Maximize | If the alternative contributes to produce and increase the revenue. (It is most preferable in case it has more potential to increase the revenue) |
| EC2-MC1 | Capital costs | Economic | Minimize | Associated costs to implement the alternative. (It is most preferable in case it has lower figure of costs) |
| EC3-MC1 | Operation & Maintenance costs | Economic | Minimize | Costs associated with control and upkeep of the alternative. (It is most preferable in case it needs low costs) |
| EC4-MC1 | Benefit period | Economic | Maximize | Measuring the useful life span of the alternative. (It is most preferable in case the alternative has longer life cycle) |
| EC5-MC2 | Water preservation & reduction of waste | Environmental | Maximize | If the alternative has the ability to maximize water savings and minimize the pressure on natural resources through reducing water losses. (It is most preferable in case its output of saving water is high) |
| EC6-MC2 | Energy saved | Environmental | Maximize | If the alternative has the ability to minimize the energy consumption and greenhouse gas emissions. (It is most preferable in case its output of saving energy is high) |
| EC7-MC3 | Supply reliability | Technical | Maximize | If the alternative has the ability to save most continuous service and minimize supply interruptions. (It is most preferable in case the proposed alternative has lower level of leaks frequencies) |
| EC8-MC3 | Flexibility | Technical | Maximize | If the alternative has the capability of being adjusted to meet varied needs and uncertainties. (It is most preferable in case the proposed option has high flexibility) |
| EC9-MC4 | Affordability | Socio-economic | Maximize | Measuring the impact of alternative on level of water tariff. (It is most preferable in case the proposed alternative has a stable effect on tariff) |
| EC10-MC4 | Water quality | Socio-economic | Maximize | Measuring the ability of alternative to improve water quality. (It is most preferable in case the proposed alternative has a strong potential to improve water quality) |

**Table B.3.** Proposed strategy alternatives which may contribute to the achievement of the objectives

| Code | Alternative | Explanations |
|---|---|---|
| Alt. 1 | Active leakage control | Which includes taking actions in the distribution system to identify and repair leaks that have not been reported (proactive control) |
| Alt. 2 | Passive leakage control | Repairing reported or evident leaks only, water loss is tackled when leakage is visible, or the problem is reported form the public (reactive control) |
| Alt. 3 | Operational pressure control & management | Managing system pressures to the optimum levels of service ensuring sufficient and efficient supply to customers, while reducing unnecessary or excess pressures, which reduces the leakage, extends useful life of infrastructure, and reduces operation and maintenance costs, using PRVs |
| Alt. 4 | Establishing district metering areas (DMAs) | Useful for improving the management of the network, monitoring the input and the output discharges, DMAs have more homogenous characteristics, and can be used to determine leakage within an area that can be isolated |
| Alt. 5 | Asset management for service lines & selective mains | Replacement of affected service lines and mains |
| Alt. 6 | Replacement of water meters | To eliminate water meter inaccuracy, may include installation of automatic water meters |
| Alt. 7 | Improving quality level of repairs & minimizing the required time of repairing | To prevent the occurrence of bursts again, and to minimize the volumes of lost water and to minimize the adverse effects of disruption of the service |
| Alt. 8 | Control of illegal use of water service | To eliminate the illegal use of water through public awareness campaigns, and effective monitoring |
| Alt. 9 | Utilizing advanced techniques to fix & predict the leakage | Useful to fix the location of leaks and to predict failures, include concrete database, hydraulic and GIS models, predicting failure models, installing pressure sensors, noise and flow sensors to monitor the variations in the network |
| Alt. 10 | Public awareness & educational campaigns | Useful to accelerate the process of fixing and repairing visible leakage and bursts and promotes the conservation measures |

## Appendix C

## Survey with decision makers (DMs)

- **Research subject:** Development of a multi-criteria decision making framework for the evaluation of water loss risk index in WSNs
- **Case Study:** Nablus Water Distribution Network (NWDN)-Nablus-Palestine
- **Used tools:** Multi criteria decision making (MCDM) techniques and simulation methods

**Background**

Water utilities in Palestine as in the most of the developing countries are struggling to reduce the gaps between available water supplies and required demands. Management of water losses in water supply networks is seen as a key to sustainable water management and in alleviating the water shortage problems. Due to insufficient financial resources and operational constraints such as the complexity and the extent of WSN, there is a need to adopt gradual improvement plans for applying the optimum strategies of managing water losses in WSNs. This entails the development of diagnostic tools to understand the conditions of different zones within WSNs and their criticality in terms of water losses. This work is seeking to develop a framework to evaluate water loss potential in different zones in water supply networks. Accordingly, the application of potential strategies to manage water losses can be applied over zones with higher priority in terms of the previous issues. This approach will contribute in developing efficient operational and adequate monitoring programs over the whole WSNs. Furthermore, it promotes the practices of long term planning instead of local actions.

The developed framework requires the identification of factors that contribute to water losses in WSNs. These factors are categorized into different categories according and arranged in a hierarchical structure of three levels. The top level is the objective of the framework. It is followed by the main categories. The basic factors are branching out from categories according to their relevance to these categories.

- **Requirements**

**1.)** Building the evaluation matrices, tow levels of evaluation matrices are built by the researcher:

**1st level**: One evaluation matrix which will include the tradeoffs, in the form of pairwise comparisons, among the main categories (physical, operational, environmental and social) in the second level of the hierarchy structure with respect to the overall objective in the top-Figure C.1.

**2nd level:** Four evaluation matrices. Each evaluation matrix will include the tradeoffs, in the form of pairwise comparisons, among each set of basic factors in the first level of the hierarchy structure with respect to their own main category in the upper level-Figure C.1.

**2.)** Used scale, the DM has to use linguistic terms, which will be converted into triangular fuzzy numbers (TFNs), in evaluating the preference of one element over another at a time (i.e. comparing the performance of one basic over another towards a specific main category). The scale is explained in Table C.1 below:

**Table C.1.** Definition of linguistic evaluation (Weight importance of main categories and basic factors)

| Linguistic variables | Code | Explanation | Positive TFN | Reciprocal TFN |
|---|---|---|---|---|
| Equal Importance | EI | Two criteria equally contribute | (1, 1, 1) | (1, 1, 1) |
| Moderate Importance | MI | Experience and judgment moderately favor one criterion over another | (1, 3, 5) | (1/5, 1/3, 1) |
| Strong Importance | SI | Experience and judgment strongly favor one criterion over another | (3, 5, 7) | (1/7, 1/5, 1/3) |
| Very Strong Importance | VSI | A criterion is favored very strongly over another | (5, 7, 9) | (1/9, 1/7, 1/5) |
| Extreme importance | EXI | A criterion is extremely favored over another | (7, 9, 9) | (1/9, 1/9, 1/7) |

**3.)** The DM has to try to ask two questions for each entry in the evaluation matrix, e.g. in case the DM wants to express his/her preferences among two basic factors with respect to a specific main category, the two questions are:

- Which is more important with respect to the category?
- How strongly?

- **Example**

Please refer to the following example which clarifies the evaluation procedure required to make tradeoffs among the basic factors of physical category -Figure C.1.

- If the DM found that the pipe diameter is with extreme importance in the physical category compared to the pipe material, the entry will be [EXI].
- If the DM found that the pipe age is with strong importance in the physical category compared to the pipe diameter, the entry will be [(SI)].
- If the DM found that the pipe length is with moderate importance in the physical category compared to the pipe diameter, the entry will be [(MI)]
- If the DM found that the pipe diameter is with moderate importance in the physical category compared to the type of traffic, the entry will be [MI].
- If the DM found that the pipe diameter is with strong importance in the physical category compared to the type of road, the entry will be [SI].

- The final filled evaluation matrix will be as follows:

| Physical category | Pipe diameter | Pipe material | Pipe age | Pipe length | Type of traffic | Type of road |
|---|---|---|---|---|---|---|
| Pipe diameter | EI | EXI | (SI)* | (MI) | MI | SI |
| Pipe material | | EI | | | | |
| Pipe age | | | EI | | | |
| Pipe length | | | | EI | | |
| Type of traffic | | | | | EI | |
| Type of road | | | | | | EI |

- For the diagonal, all values are EI as the comparison between the elements themselves.
- Under the diagonal, the values will be reciprocal to the values above the diagonal (no need to fill under the diagonal in the evaluation matrix, it is the responsibility of the researcher to complete these entries).

- Please refer to the following items before proceeding with the evaluation process:
  -Figure C.1, which illustrates the hierarchy structure of the decision problem,
  -Table C.2, which explains in details the main categories and their basic factors

- Please try to express your preferences as a DM in the following decision matrices.

**Level of main categories:** Please make pairwise comparisons between each two elements at a time (two main category) with respect to the overall objective by using the linguistic terms in Table C.1. No need to fill in the diagonal and under the diagonal.

| Overall Objective | Physical category | Operational category | Environmental category | Social category |
|---|---|---|---|---|
| Physical category | EI | | | |
| Operational category | | EI | | |
| Environmental category | | | EI | |
| Social category | | | | EI |

**Level of basic factors:** Please make pairwise comparisons between each two elements at a time (two basic factors) with respect to their own category by using the linguistic terms in Table C.1. No need to fill in the diagonal and under the diagonal.

| Physical category | Pipe diameter | Pipe material | Pipe age | Pipe length | Type of traffic | Type of road |
|---|---|---|---|---|---|---|
| Pipe diameter | EI | | | | | |
| Pipe material | | EI | | | | |
| Pipe age | | | EI | | | |
| Pipe length | | | | EI | | |
| Type of traffic | | | | | EI | |
| Type of road | | | | | | EI |

| Operational category | Pressure | Water Velocity | No. of breaks | Water meters | Average supply hours | Service connections |
|---|---|---|---|---|---|---|
| Pressure | EI | | | | | |
| Water Velocity | | EI | | | | |
| No. of breaks | | | EI | | | |
| Water meters | | | | EI | | |
| Average supply hours | | | | | EI | |
| Service connections | | | | | | EI |

| Environmental category | Quality of water | Impact on public health | Damage to surrounding |
|---|---|---|---|
| Quality of water | EI | | |
| Impact on public health | | EI | |
| Damage to surrounding | | | EI |

| Social category | Type of consumption | Density of population | Public economies |
|---|---|---|---|
| Type of consumption | EI | | |
| Density of population | | EI | |
| Public economies | | | EI |

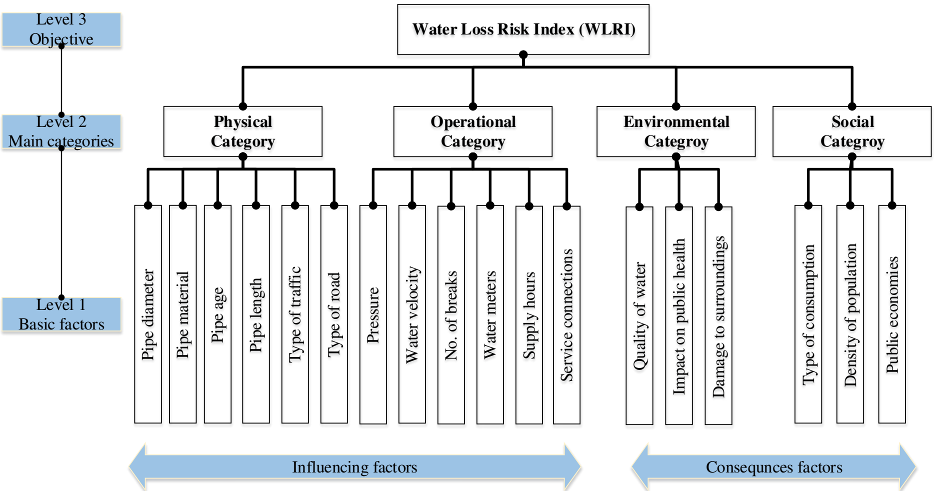


**Figure C.1** Hierarchical structure of contributing factors to water loss risk index (WLRI) in water distribution networks.

**Table C.2** Contributing factors to water loss risk index (WLRI) in water distribution networks identified from previous studies

| Category | Factors | Description |
|---|---|---|
| Physical | | |
| | Pipe diameter (mm) | Pipes with larger diameters are less prone to failures than pipes with smaller diameters |
| | Pipe material | Different materials are failed in different ways |
| | Pipe age (year) | The effects of pipe degradation become more apparent over time |
| | Pipe length (m) | Pipes with larger lengths are more prone to failures than pipes with smaller lengths |
| | Type of traffic | The rates of failures increase proportionally with traffic loads |
| | Type of road | The condition of the road under which the pipe passes affects the rates of failure |
| Operational | | |
| | Pressure (m) | The changes in the internal pressure will change stress acting on the pipes |
| | Water Velocity (m/s) | High velocities corrode the internal walls of pipes |
| | No. of breaks (breaks/km/year) | High breakage rates indicate a poor condition of pipe lines |
| | Water meters (No.) | The increase of density of water meters indicates that, higher apparent losses are expected |
| | Average supply hours (hours/day) | The increase in the duration of water supply leads to less chances of pipe failure |
| | Service connections (No.) | The increase of density of water services indicates that, the risk of the pipe getting structurally worse is more |
| Environmental | | |
| | Quality of water | The degree of risk from contamination by infiltration |
| | Impact on public health (No. of illness) | The associated health risks from contaminated water and their effects on public safety |
| | Damage to surrounding | Potential property damage and traffic disruption |
| Social | | |
| | Type of consumption | The importance of the served category (i.e. residential, commercial, industrial) with high importance of residential category |
| | Density of population (No.) | The effect of failure is more critical in case there is high density of served people |
| | Public economies | This indicates the importance of served area, the importance is proportional with the increase in number of public economies |

# Appendix D

**Table D.1** Absolute, relative priorities and total weighting of alternatives of MCDM of water loss management -DM1 (Palestinian Water Authority (PWA)-Directorate of Research & Development/Economic & Tariff Department)

| Level 2 and 3[a] | | | | Level 4[b] | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *WAi* | | | | *Alt. 1* | | *Alt. 2* | | *Alt. 3* | | *Alt. 4* | | *Alt. 5* | | *Alt. 6* | | *Alt. 7* | | *Alt. 8* | | *Alt. 9* | | *Alt. 10* | |
| **MC1 (Eco)** | 0.263 | LP[c] | GP[d] | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP |
| *EC1-MC1* | | 0.399 | 0.105 | 0.212 | 0.022 | 0.223 | 0.023 | 0.055 | 0.006 | 0.159 | 0.017 | 0.106 | 0.011 | 0.102 | 0.011 | 0.057 | 0.006 | 0.034 | 0.004 | 0.025 | 0.003 | 0.027 | 0.003 |
| *EC2-MC1* | | 0.357 | 0.094 | 0.155 | 0.015 | 0.188 | 0.018 | 0.079 | 0.007 | 0.210 | 0.020 | 0.070 | 0.007 | 0.056 | 0.005 | 0.068 | 0.006 | 0.032 | 0.003 | 0.043 | 0.004 | 0.099 | 0.009 |
| *EC3-MC1* | | 0.161 | 0.042 | 0.158 | 0.007 | 0.190 | 0.008 | 0.100 | 0.004 | 0.205 | 0.009 | 0.036 | 0.002 | 0.055 | 0.002 | 0.067 | 0.003 | 0.055 | 0.002 | 0.048 | 0.002 | 0.087 | 0.004 |
| *EC4-MC1* | | 0.083 | 0.022 | 0.21 | 0.005 | 0.206 | 0.004 | 0.069 | 0.002 | 0.152 | 0.003 | 0.105 | 0.002 | 0.102 | 0.002 | 0.058 | 0.001 | 0.044 | 0.001 | 0.028 | 0.001 | 0.026 | 0.001 |
| ***MC2* (Env)** | 0.122 | | | | | | | | | | | | | | | | | | | | | | |
| *EC5-MC2* | | 0.25 | 0.031 | 0.022 | 0.001 | 0.022 | 0.001 | 0.077 | 0.002 | 0.214 | 0.007 | 0.093 | 0.003 | 0.053 | 0.002 | 0.123 | 0.004 | 0.053 | 0.002 | 0.269 | 0.008 | 0.074 | 0.002 |
| *EC6-MC2* | | 0.75 | 0.092 | 0.026 | 0.002 | 0.021 | 0.002 | 0.087 | 0.008 | 0.174 | 0.016 | 0.132 | 0.012 | 0.041 | 0.004 | 0.106 | 0.010 | 0.035 | 0.003 | 0.300 | 0.027 | 0.079 | 0.007 |
| ***MC3* (Tech)** | 0.057 | | | | | | | | | | | | | | | | | | | | | | |
| *EC7-MC3* | | 0.75 | 0.043 | 0.024 | 0.001 | 0.025 | 0.001 | 0.241 | 0.010 | 0.070 | 0.003 | 0.233 | 0.010 | 0.105 | 0.004 | 0.113 | 0.005 | 0.090 | 0.004 | 0.066 | 0.003 | 0.034 | 0.001 |
| *EC8-MC3* | | 0.25 | 0.014 | 0.026 | 0.0004 | 0.025 | 0.0004 | 0.226 | 0.003 | 0.078 | 0.001 | 0.229 | 0.003 | 0.128 | 0.002 | 0.078 | 0.001 | 0.099 | 0.001 | 0.073 | 0.001 | 0.038 | 0.001 |
| ***MC4* (Socio)** | 0.558 | | | | | | | | | | | | | | | | | | | | | | |
| *EC9-MC4* | | 0.50 | 0.279 | 0.07 | 0.020 | 0.110 | 0.031 | 0.228 | 0.064 | 0.124 | 0.035 | 0.170 | 0.047 | 0.109 | 0.030 | 0.051 | 0.014 | 0.054 | 0.015 | 0.028 | 0.008 | 0.055 | 0.015 |
| *EC10-MC4* | | 0.50 | 0.279 | 0.036 | 0.010 | 0.066 | 0.018 | 0.153 | 0.043 | 0.092 | 0.026 | 0.105 | 0.029 | 0.061 | 0.017 | 0.031 | 0.009 | 0.038 | 0.011 | 0.377 | 0.105 | 0.041 | 0.011 |
| Overall weight | | | | | **0.082** | | **0.107** | | **0.149** | | **0.135** | | **0.126** | | **0.080** | | **0.059** | | **0.046** | | **0.162** | | **0.055** |
| Ranking the set of alternatives | | | | | **6th** | | **5th** | | **2nd** | | **3rd** | | **4th** | | **7th** | | **8th** | | **10th** | | **1st** | | **9th** |

[a]The inputs of this column represent the weights of main criteria under the overall goal in the hierarchy structure, and sub-criteria (evaluation criteria) under the criteria.

[b]These inputs represent the weights of alternatives.

[c]LP represents the local weight or percentage.

[d]GP represents the global weight or percentage.

**Table D.2** Absolute, relative priorities and total weighting of alternatives of MCDM of water loss management- DM2 (Palestinian Water Authority (PWA)-Directorate of Research & Development/Water Control Directorate)

| **Level 2 and 3**[a] | | | | **Level 4**[b] | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | ***Alt. 1*** | | ***Alt. 2*** | | ***Alt. 3*** | | ***Alt. 4*** | | ***Alt. 5*** | | ***Alt. 6*** | | ***Alt. 7*** | | ***Alt. 8*** | | ***Alt. 9*** | | ***Alt. 10*** | |
| ***WAi*** | | | | | | | | | | | | | | | | | | | | | | | |
| **MC1 (Eco)** | 0.661 | LP[c] | GP[d] | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP |
| *EC1-MC1* | | 0.584 | 0.386 | 0.15 | 0.058 | 0.110 | 0.042 | 0.230 | 0.089 | 0.070 | 0.027 | 0.100 | 0.039 | 0.200 | 0.077 | 0.030 | 0.012 | 0.020 | 0.008 | 0.050 | 0.019 | 0.020 | 0.008 |
| *EC2-MC1* | | 0.255 | 0.169 | 0.14 | 0.024 | 0.090 | 0.015 | 0.220 | 0.037 | 0.090 | 0.015 | 0.060 | 0.010 | 0.230 | 0.039 | 0.030 | 0.005 | 0.020 | 0.003 | 0.100 | 0.017 | 0.020 | 0.003 |
| *EC3-MC1* | | 0.12 | 0.079 | 0.15 | 0.012 | 0.110 | 0.009 | 0.200 | 0.016 | 0.110 | 0.009 | 0.040 | 0.003 | 0.160 | 0.013 | 0.040 | 0.003 | 0.030 | 0.002 | 0.150 | 0.012 | 0.020 | 0.002 |
| *EC4-MC1* | | 0.041 | 0.027 | 0.083 | 0.002 | 0.047 | 0.001 | 0.124 | 0.003 | 0.113 | 0.003 | 0.189 | 0.005 | 0.181 | 0.005 | 0.057 | 0.002 | 0.035 | 0.001 | 0.147 | 0.004 | 0.025 | 0.001 |
| ***MC2* (Env)** | 0.199 | | | | | | | | | | | | | | | | | | | | | | |
| *EC5-MC2* | | 0.90 | 0.179 | 0.087 | 0.016 | 0.033 | 0.006 | 0.190 | 0.034 | 0.177 | 0.032 | 0.138 | 0.025 | 0.114 | 0.020 | 0.047 | 0.008 | 0.064 | 0.011 | 0.124 | 0.022 | 0.027 | 0.005 |
| *EC6-MC2* | | 0.10 | 0.02 | 0.127 | 0.003 | 0.207 | 0.004 | 0.120 | 0.002 | 0.090 | 0.002 | 0.112 | 0.002 | 0.145 | 0.003 | 0.048 | 0.001 | 0.039 | 0.001 | 0.089 | 0.002 | 0.023 | 0.000 |
| ***MC3* (Tech)** | 0.093 | | | | | | | | | | | | | | | | | | | | | | |
| *EC7-MC3* | | 0.875 | 0.081 | 0.159 | 0.013 | 0.028 | 0.002 | 0.171 | 0.014 | 0.082 | 0.007 | 0.194 | 0.016 | 0.082 | 0.007 | 0.072 | 0.006 | 0.088 | 0.007 | 0.097 | 0.008 | 0.027 | 0.002 |
| *EC8-MC3* | | 0.125 | 0.012 | 0.044 | 0.0005 | 0.035 | 0.0004 | 0.191 | 0.002 | 0.119 | 0.001 | 0.152 | 0.002 | 0.160 | 0.002 | 0.077 | 0.001 | 0.108 | 0.001 | 0.087 | 0.001 | 0.027 | 0.000 |
| ***MC4* (Socio)** | 0.047 | | | | | | | | | | | | | | | | | | | | | | |
| *EC9-MC4* | | 0.88 | 0.041 | 0.121 | 0.005 | 0.226 | 0.009 | 0.118 | 0.005 | 0.103 | 0.004 | 0.142 | 0.006 | 0.107 | 0.004 | 0.045 | 0.002 | 0.049 | 0.002 | 0.066 | 0.003 | 0.023 | 0.001 |
| *EC10-MC4* | | 0.13 | 0.06 | 0.04 | 0.000 | 0.070 | 0.000 | 0.180 | 0.001 | 0.110 | 0.001 | 0.140 | 0.001 | 0.070 | 0.000 | 0.030 | 0.000 | 0.040 | 0.000 | 0.270 | 0.002 | 0.050 | 0.000 |
| Overall weight | | | | | **0.132** | | **0.090** | | **0.204** | | **0.100** | | **0.108** | | **0.170** | | **0.040** | | **0.037** | | **0.089** | | **0.022** |
| Ranking the set of alternatives | | | | | **3rd** | | **6th** | | **1st** | | **5th** | | **4th** | | **2nd** | | **8th** | | **9th** | | **7th** | | **10th** |

[a]The inputs of this column represent the weights of main criteria under the overall goal in the hierarchy structure, and sub-criteria (evaluation criteria) under the criteria.

[b]These inputs represent the weights of alternatives.

[c]LP represents the local weight or percentage.

[d]GP represents the global weight or percentage.

**Table D.3** Absolute, relative priorities and total weighting of alternatives of MCDM of water loss management-DM3 (Palestinian Hydrology Group (PHG) - Non Governmental Organization)

| **Level 2 and 3[a]** | | | | **Level 4[b]** | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | ***Alt. 1*** | | ***Alt. 2*** | | ***Alt. 3*** | | ***Alt. 4*** | | ***Alt. 5*** | | ***Alt. 6*** | | ***Alt. 7*** | | ***Alt. 8*** | | ***Alt. 9*** | | ***Alt. 10*** | |
| ***WAi*** | | | | | | | | | | | | | | | | | | | | | | | |
| **MC1 (Eco)** | 0.126 | LP[c] | GP[d] | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP |
| *EC1-MC1* | | 0.224 | 0.028 | 0.255 | 0.007 | 0.185 | 0.005 | 0.094 | 0.003 | 0.136 | 0.004 | 0.084 | 0.002 | 0.082 | 0.002 | 0.068 | 0.002 | 0.044 | 0.001 | 0.026 | 0.001 | 0.027 | 0.001 |
| *EC2-MC1* | | 0.130 | 0.016 | 0.14 | 0.002 | 0.192 | 0.003 | 0.139 | 0.002 | 0.156 | 0.003 | 0.071 | 0.001 | 0.055 | 0.001 | 0.071 | 0.001 | 0.033 | 0.001 | 0.044 | 0.001 | 0.092 | 0.002 |
| *EC3-MC1* | | 0.485 | 0.061 | 0.05 | 0.003 | 0.044 | 0.003 | 0.137 | 0.008 | 0.130 | 0.008 | 0.168 | 0.010 | 0.071 | 0.004 | 0.082 | 0.005 | 0.065 | 0.004 | 0.227 | 0.014 | 0.026 | 0.002 |
| *EC4-MC1* | | 0.161 | 0.02 | 0.053 | 0.001 | 0.027 | 0.001 | 0.125 | 0.003 | 0.138 | 0.003 | 0.206 | 0.004 | 0.103 | 0.002 | 0.109 | 0.002 | 0.059 | 0.001 | 0.156 | 0.003 | 0.024 | 0.0005 |
| ***MC2* (Env)** | 0.474 | | | | | | | | | | | | | | | | | | | | | | |
| *EC5-MC2* | | 0.83 | 0.397 | 0.13 | 0.052 | 0.022 | 0.009 | 0.132 | 0.052 | 0.155 | 0.062 | 0.193 | 0.077 | 0.057 | 0.023 | 0.073 | 0.029 | 0.041 | 0.016 | 0.150 | 0.060 | 0.045 | 0.018 |
| *EC6-MC2* | | 0.17 | 0.08 | 0.03 | 0.002 | 0.037 | 0.003 | 0.127 | 0.010 | 0.157 | 0.013 | 0.215 | 0.017 | 0.065 | 0.005 | 0.097 | 0.008 | 0.053 | 0.004 | 0.193 | 0.015 | 0.026 | 0.002 |
| ***MC3* (Tech)** | 0.067 | | | | | | | | | | | | | | | | | | | | | | |
| *EC7-MC3* | | 0.875 | 0.059 | 0.11 | 0.006 | 0.029 | 0.002 | 0.218 | 0.013 | 0.109 | 0.006 | 0.155 | 0.009 | 0.086 | 0.005 | 0.087 | 0.005 | 0.050 | 0.003 | 0.138 | 0.008 | 0.019 | 0.001 |
| *EC8-MC3* | | 0.125 | 0.008 | 0.178 | 0.0015 | 0.042 | 0.0004 | 0.131 | 0.001 | 0.151 | 0.001 | 0.083 | 0.001 | 0.054 | 0.0005 | 0.106 | 0.001 | 0.050 | 0.000 | 0.178 | 0.001 | 0.027 | 0.0002 |
| ***MC4* (Socio)** | 0.329 | | | | | | | | | | | | | | | | | | | | | | |
| *EC9-MC4* | | 0.10 | 0.033 | 0.105 | 0.003 | 0.077 | 0.003 | 0.159 | 0.005 | 0.164 | 0.005 | 0.068 | 0.002 | 0.059 | 0.002 | 0.117 | 0.004 | 0.054 | 0.002 | 0.171 | 0.006 | 0.026 | 0.001 |
| *EC10-MC4* | | 0.90 | 0.296 | 0.16 | 0.047 | 0.031 | 0.009 | 0.107 | 0.032 | 0.109 | 0.032 | 0.239 | 0.071 | 0.059 | 0.017 | 0.089 | 0.026 | 0.048 | 0.014 | 0.136 | 0.040 | 0.022 | 0.007 |
| Overall weight | | | | | **0.126** | | **0.037** | | **0.129** | | **0.137** | | **0.195** | | **0.062** | | **0.083** | | **0.047** | | **0.149** | | **0.033** |
| Ranking the set of alternatives | | | | | **5th** | | **9th** | | **4th** | | **3rd** | | **1st** | | **7th** | | **6th** | | **8th** | | **2nd** | | **10th** |

[a]The inputs of this column represent the weights of main criteria under the overall goal in the hierarchy structure, and sub-criteria (evaluation criteria) under the criteria.

[b]These inputs represent the weights of alternatives.

[c]LP represents the local weight or percentage.

[d]GP represents the global weight or percentage.

**Table D.4** Absolute, relative priorities and total weighting of alternatives of MCDM of water loss management -DM4 (Water & Sanitation Department-Nablus Municipality (WSDN)

| Level 2 and 3[a] | | | | Level 4[b] | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *WAi* | | | | *Alt. 1* | | *Alt. 2* | | *Alt. 3* | | *Alt. 4* | | *Alt. 5* | | *Alt. 6* | | *Alt. 7* | | *Alt. 8* | | *Alt. 9* | | *Alt. 10* | |
| **MC1 (Eco)** | 0.69 | LP[c] | GP[d] | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP |
| *EC1-MC1* | | 0.623 | 0.43 | 0.066 | 0.028 | 0.044 | 0.019 | 0.274 | 0.118 | 0.170 | 0.073 | 0.023 | 0.010 | 0.143 | 0.061 | 0.070 | 0.030 | 0.036 | 0.015 | 0.146 | 0.063 | 0.029 | 0.012 |
| *EC2-MC1* | | 0.242 | 0.167 | 0.044 | 0.007 | 0.024 | 0.004 | 0.120 | 0.020 | 0.119 | 0.020 | 0.300 | 0.050 | 0.112 | 0.019 | 0.035 | 0.006 | 0.056 | 0.009 | 0.176 | 0.029 | 0.016 | 0.003 |
| *EC3-MC1* | | 0.094 | 0.065 | 0.056 | 0.004 | 0.024 | 0.002 | 0.188 | 0.012 | 0.213 | 0.014 | 0.217 | 0.014 | 0.086 | 0.006 | 0.048 | 0.003 | 0.030 | 0.002 | 0.116 | 0.008 | 0.023 | 0.001 |
| *EC4-MC1* | | 0.042 | 0.029 | 0.05 | 0.001 | 0.018 | 0.001 | 0.106 | 0.003 | 0.121 | 0.004 | 0.259 | 0.008 | 0.132 | 0.004 | 0.062 | 0.002 | 0.048 | 0.001 | 0.176 | 0.005 | 0.027 | 0.0008 |
| ***MC2* (Env)** | 0.122 | | | | | | | | | | | | | | | | | | | | | | |
| *EC5-MC2* | | 0.875 | 0.107 | 0.067 | 0.007 | 0.020 | 0.002 | 0.141 | 0.015 | 0.107 | 0.011 | 0.224 | 0.024 | 0.143 | 0.015 | 0.057 | 0.006 | 0.046 | 0.005 | 0.174 | 0.019 | 0.022 | 0.002 |
| *EC6-MC2* | | 0.125 | 0.015 | 0.046 | 0.001 | 0.035 | 0.001 | 0.144 | 0.002 | 0.144 | 0.002 | 0.139 | 0.002 | 0.124 | 0.002 | 0.081 | 0.001 | 0.035 | 0.001 | 0.229 | 0.003 | 0.024 | 0.0004 |
| ***MC3* (Tech)** | 0.128 | | | | | | | | | | | | | | | | | | | | | | |
| *EC7-MC3* | | 0.875 | 0.112 | 0.051 | 0.006 | 0.032 | 0.004 | 0.159 | 0.018 | 0.175 | 0.020 | 0.125 | 0.014 | 0.150 | 0.017 | 0.072 | 0.008 | 0.050 | 0.006 | 0.163 | 0.018 | 0.022 | 0.002 |
| *EC8-MC3* | | 0.125 | 0.016 | 0.068 | 0.0011 | 0.025 | 0.0004 | 0.144 | 0.002 | 0.167 | 0.003 | 0.125 | 0.002 | 0.135 | 0.0022 | 0.083 | 0.001 | 0.033 | 0.001 | 0.195 | 0.003 | 0.025 | 0.0004 |
| ***MC4* (Socio)** | 0.06 | | | | | | | | | | | | | | | | | | | | | | |
| *EC9-MC4* | | 0.25 | 0.015 | 0.088 | 0.001 | 0.135 | 0.002 | 0.140 | 0.002 | 0.148 | 0.002 | 0.053 | 0.001 | 0.214 | 0.003 | 0.096 | 0.001 | 0.047 | 0.001 | 0.058 | 0.001 | 0.022 | 0.0003 |
| *EC10-MC4* | | 0.75 | 0.045 | 0.102 | 0.005 | 0.048 | 0.002 | 0.114 | 0.005 | 0.096 | 0.004 | 0.163 | 0.007 | 0.262 | 0.012 | 0.080 | 0.004 | 0.048 | 0.002 | 0.062 | 0.003 | 0.025 | 0.001 |
| Overall weight | | | | | **0.061** | | **0.036** | | **0.198** | | **0.153** | | **0.132** | | **0.141** | | **0.063** | | **0.043** | | **0.152** | | **0.024** |
| Ranking the set of alternatives | | | | | **7th** | | **9th** | | **1st** | | **2nd** | | **5th** | | **4th** | | **6th** | | **8th** | | **3rd** | | **10th** |

[a]The inputs of this column represent the weights of main criteria under the overall goal in the hierarchy structure, and sub-criteria (evaluation criteria) under the criteria.

[b]These inputs represent the weights of alternatives.

[c]LP represents the local weight or percentage.

[d]GP represents the global weight or percentage.

**Table D.5** Absolute, relative priorities and total weighting of alternatives of MCDM of water loss management resulted from aggregation of preferences of all groups of DMs by geometric mean method (GMM) technique

| Level 2 and 3[a] | | | | Level 4[b] | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *WA*i | | | | *Alt. 1* | | *Alt. 2* | | *Alt. 3* | | *Alt. 4* | | *Alt. 5* | | *Alt. 6* | | *Alt. 7* | | *Alt. 8* | | *Alt. 9* | | *Alt. 10* | |
| **MC1 (Eco)** | 0.461 | LP[c] | GP[d] | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP |
| *EC1-MC1* | | 0.477 | 0.218 | 0.1774 | 0.039 | 0.133 | 0.029 | 0.151 | 0.033 | 0.146 | 0.032 | 0.072 | 0.016 | 0.139 | 0.030 | 0.060 | 0.013 | 0.036 | 0.008 | 0.056 | 0.012 | 0.029 | 0.006 |
| *EC2-MC1* | | 0.255 | 0.116 | 0.1232 | 0.014 | 0.110 | 0.013 | 0.152 | 0.018 | 0.161 | 0.019 | 0.114 | 0.013 | 0.112 | 0.013 | 0.053 | 0.006 | 0.038 | 0.004 | 0.092 | 0.011 | 0.045 | 0.005 |
| *EC3-MC1* | | 0.192 | 0.088 | 0.1011 | 0.009 | 0.077 | 0.007 | 0.170 | 0.015 | 0.182 | 0.016 | 0.096 | 0.008 | 0.098 | 0.009 | 0.064 | 0.006 | 0.047 | 0.004 | 0.131 | 0.012 | 0.034 | 0.003 |
| *EC4-MC1* | | 0.076 | 0.035 | 0.0892 | 0.003 | 0.050 | 0.002 | 0.110 | 0.004 | 0.145 | 0.005 | 0.203 | 0.007 | 0.139 | 0.005 | 0.073 | 0.003 | 0.050 | 0.002 | 0.113 | 0.004 | 0.027 | 0.001 |
| ***MC2* (Env)** | 0.245 | | | | | | | | | | | | | | | | | | | | | | |
| *EC5-MC2* | | 0.762 | 0.187 | 0.0664 | 0.012 | 0.025 | 0.005 | 0.139 | 0.026 | 0.171 | 0.032 | 0.163 | 0.030 | 0.087 | 0.016 | 0.074 | 0.014 | 0.052 | 0.010 | 0.184 | 0.034 | 0.039 | 0.007 |
| *EC6-MC2* | | 0.238 | 0.058 | 0.0496 | 0.003 | 0.054 | 0.003 | 0.129 | 0.008 | 0.154 | 0.009 | 0.156 | 0.009 | 0.092 | 0.005 | 0.086 | 0.005 | 0.043 | 0.003 | 0.202 | 0.012 | 0.035 | 0.002 |
| ***MC3* (Tech)** | 0.102 | | | | | | | | | | | | | | | | | | | | | | |
| *EC7-MC3* | | 0.85 | 0.089 | 0.0671 | 0.006 | 0.029 | 0.003 | 0.209 | 0.019 | 0.106 | 0.009 | 0.186 | 0.017 | 0.108 | 0.010 | 0.088 | 0.008 | 0.068 | 0.006 | 0.112 | 0.010 | 0.026 | 0.002 |
| *EC8-MC3* | | 0.15 | 0.016 | 0.0627 | 0.001 | 0.032 | 0.001 | 0.185 | 0.003 | 0.134 | 0.002 | 0.145 | 0.002 | 0.122 | 0.002 | 0.092 | 0.001 | 0.067 | 0.001 | 0.129 | 0.002 | 0.031 | 0.000 |
| ***MC4* (Socio)** | 0.192 | | | | | | | | | | | | | | | | | | | | | | |
| *EC9-MC4* | | 0.42 | 0.081 | 0.0955 | 0.008 | 0.134 | 0.011 | 0.172 | 0.014 | 0.147 | 0.012 | 0.104 | 0.008 | 0.120 | 0.010 | 0.075 | 0.006 | 0.053 | 0.004 | 0.067 | 0.005 | 0.031 | 0.002 |
| *EC10-MC4* | | 0.58 | 0.110 | 0.078 | 0.009 | 0.055 | 0.006 | 0.152 | 0.017 | 0.115 | 0.013 | 0.168 | 0.019 | 0.102 | 0.012 | 0.060 | 0.007 | 0.049 | 0.006 | 0.185 | 0.021 | 0.037 | 0.004 |
| Overall weight | | | | | **0.104** | | **0.078** | | **0.155** | | **0.149** | | **0.130** | | **0.111** | | **0.068** | | **0.047** | | **0.123** | | **0.034** |
| Ranking the set of alternatives | | | | | **6th** | | **7th** | | **1st** | | **2nd** | | **3rd** | | **5th** | | **8th** | | **9th** | | **4th** | | **10th** |

[a]The inputs of this column represent the weights of main criteria under the overall goal in the hierarchy structure, and sub-criteria (evaluation criteria) under the criteria.

[b]These inputs represent the weights of alternatives.

[c]LP represents the local weight or percentage.

[d]GP represents the global weight or percentage.

**Table D.6** Absolute, relative priorities and total weighting of alternatives of MCDM of water loss management resulted from aggregation of preferences of all groups of DMs by weighted arithmetic mean method (WAMM) technique

| **Level 2 and 3**[a] | | | | **Level 4**[b] | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***WAi*** | | | | ***Alt. 1*** | | ***Alt. 2*** | | ***Alt. 3*** | | ***Alt. 4*** | | ***Alt. 5*** | | ***Alt. 6*** | | ***Alt. 7*** | | ***Alt. 8*** | | ***Alt. 9*** | | ***Alt. 10*** | |
| **MC1 (Eco)** | 0.435 | LP[c] | GP[d] | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP | LP | GP |
| *EC1-MC1* | | 0.458 | 0.199 | 0.1708 | 0.034 | 0.141 | 0.028 | 0.163 | 0.032 | 0.134 | 0.027 | 0.078 | 0.016 | 0.132 | 0.026 | 0.056 | 0.011 | 0.034 | 0.007 | 0.062 | 0.012 | 0.026 | 0.005 |
| *EC2-MC1* | | 0.246 | 0.107 | 0.1198 | 0.013 | 0.124 | 0.013 | 0.140 | 0.015 | 0.144 | 0.015 | 0.125 | 0.013 | 0.113 | 0.012 | 0.051 | 0.005 | 0.035 | 0.004 | 0.091 | 0.010 | 0.057 | 0.006 |
| *EC3-MC1* | | 0.215 | 0.094 | 0.1035 | 0.010 | 0.092 | 0.009 | 0.156 | 0.015 | 0.165 | 0.015 | 0.115 | 0.011 | 0.093 | 0.009 | 0.059 | 0.006 | 0.045 | 0.004 | 0.135 | 0.013 | 0.039 | 0.004 |
| *EC4-MC1* | | 0.082 | 0.036 | 0.099 | 0.004 | 0.075 | 0.003 | 0.106 | 0.004 | 0.131 | 0.005 | 0.190 | 0.007 | 0.130 | 0.005 | 0.072 | 0.003 | 0.047 | 0.002 | 0.127 | 0.005 | 0.026 | 0.001 |
| ***MC2* (Env)** | 0.229 | | | | | | | | | | | | | | | | | | | | | | |
| *EC5-MC2* | | 0.715 | 0.117 | 0.0765 | 0.009 | 0.024 | 0.003 | 0.135 | 0.016 | 0.163 | 0.019 | 0.162 | 0.019 | 0.092 | 0.011 | 0.075 | 0.009 | 0.051 | 0.006 | 0.179 | 0.021 | 0.042 | 0.005 |
| *EC6-MC2* | | 0.286 | 0.065 | 0.0573 | 0.004 | 0.075 | 0.005 | 0.120 | 0.008 | 0.141 | 0.009 | 0.150 | 0.010 | 0.094 | 0.006 | 0.083 | 0.005 | 0.041 | 0.003 | 0.203 | 0.013 | 0.038 | 0.002 |
| ***MC3* (Tech)** | 0.086 | | | | | | | | | | | | | | | | | | | | | | |
| *EC7-MC3* | | 0.844 | 0.073 | 0.086 | 0.006 | 0.029 | 0.002 | 0.197 | 0.014 | 0.109 | 0.008 | 0.177 | 0.013 | 0.106 | 0.008 | 0.086 | 0.006 | 0.070 | 0.005 | 0.116 | 0.008 | 0.026 | 0.002 |
| *EC8-MC3* | | 0.156 | 0.013 | 0.079 | 0.001 | 0.032 | 0.0004 | 0.173 | 0.002 | 0.129 | 0.002 | 0.147 | 0.002 | 0.119 | 0.002 | 0.086 | 0.001 | 0.073 | 0.001 | 0.133 | 0.002 | 0.029 | 0.0004 |
| ***MC4* (Socio)** | 0.249 | | | | | | | | | | | | | | | | | | | | | | |
| *EC9-MC4* | | 0.43 | 0.107 | 0.096 | 0.010 | 0.137 | 0.015 | 0.161 | 0.017 | 0.135 | 0.014 | 0.108 | 0.012 | 0.122 | 0.013 | 0.077 | 0.008 | 0.051 | 0.005 | 0.081 | 0.009 | 0.032 | 0.003 |
| *EC10-MC4* | | 0.57 | 0.141 | 0.0845 | 0.012 | 0.054 | 0.008 | 0.139 | 0.020 | 0.102 | 0.014 | 0.162 | 0.023 | 0.113 | 0.016 | 0.058 | 0.008 | 0.044 | 0.006 | 0.211 | 0.030 | 0.035 | 0.005 |
| Overall weight | | | | | **0.102** | | **0.085** | | **0.143** | | **0.129** | | **0.125** | | **0.107** | | **0.063** | | **0.043** | | **0.122** | | **0.034** |
| Ranking the set of alternatives | | | | | **6th** | | **7th** | | **1st** | | **2nd** | | **3rd** | | **5th** | | **8th** | | **9th** | | **4th** | | **10th** |

[a]The inputs of this column represent the weights of main criteria under the overall goal in the hierarchy structure, and sub-criteria (evaluation criteria) under the criteria.

[b]These inputs represent the weights of alternatives.

[c]LP represents the local weight or percentage.

[d]GP represents the global weight or percentage.

## Appendix E

**Results of dynamic sensitivity analysis for the four main criteria under the overall goal**

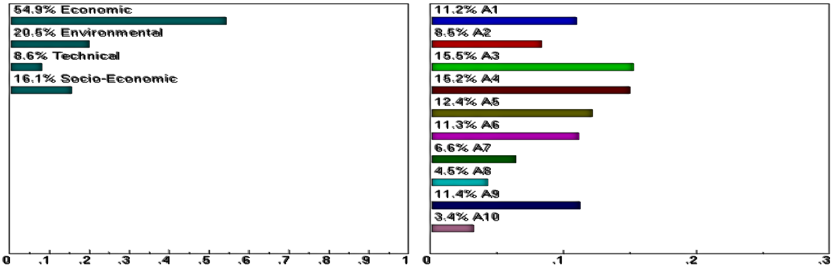


**Figure E1 |** Dynamic sensitivity analysis for **economic criterion** – **maximum limit** of stability interval.

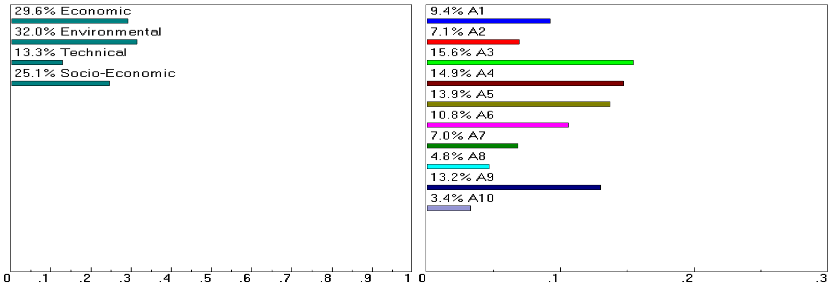


**Figure E2 |** Dynamic sensitivity analysis for **economic criterion** – **minimum limit** of stability interval.

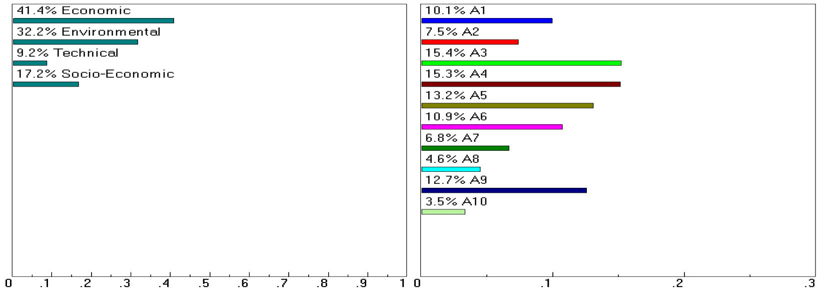


**Figure E3 |** Dynamic sensitivity analysis for **environmental criterion – maximum limit** of stability interval.

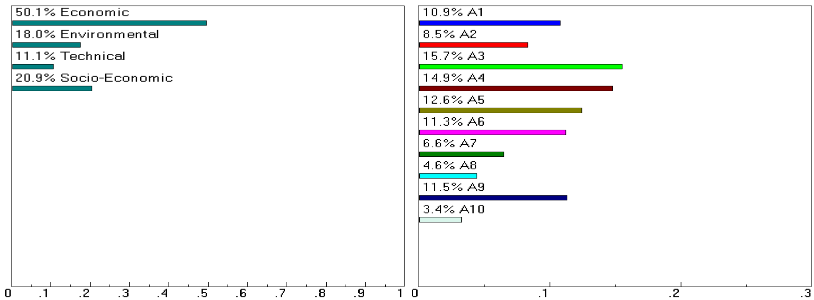


**Figure E4 |** Dynamic sensitivity analysis for environmental node – minimum limit of stability interval.

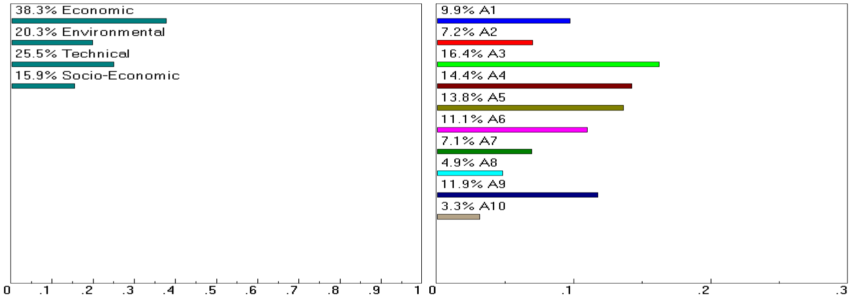


**Figure E5 |** Dynamic sensitivity analysis for **technical criterion – maximum limit** of stability interval.

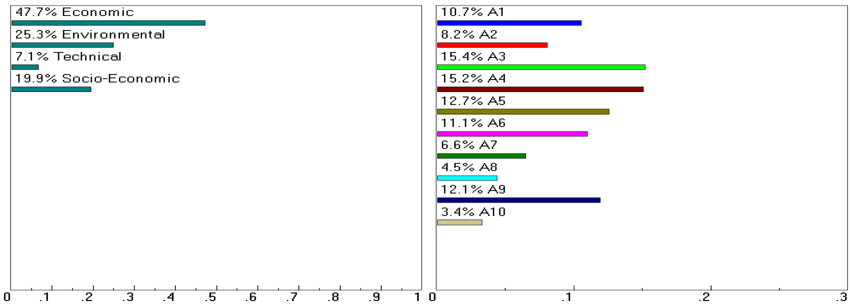


**Figure E6 |** Dynamic sensitivity analysis for **technical criterion – minimum limit** of stability interval.

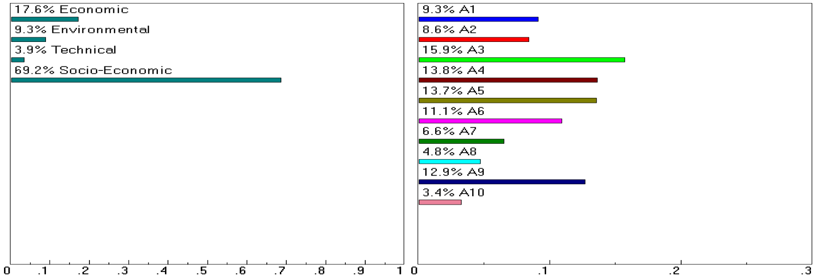


**Figure E7 |** Dynamic sensitivity analysis for **socio-economic criterion – maximum limit** of stability interval.

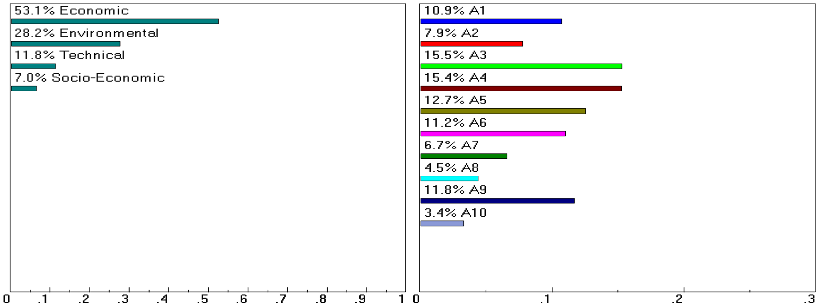


**Figure E8 |** Dynamic sensitivity analysis for **socio-economic criterion – minimum limit** of stability interval.

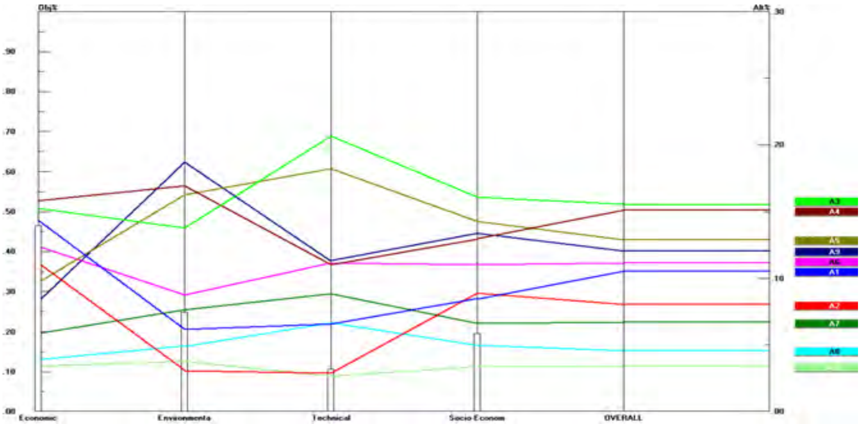


**Figure E9 |** Performance sensitivity analysis for the main criteria.

## Appendix F

Priority weights of main criteria (MC1 to MC4), evaluation criteria (EC1-MC1 to EC10-MC4) and alternatives (Alt. 1 to Alt. 10) by traditional AHP techniques (AHP-GMM and AHP- WAMM) and Fuzzy AHP techniques (FAHP-WAM1; FAHP- WAM2; FAHP-WAM3-FAHP and Modified FAHP)

**Level 2 - Priority weights of main criteria**

| Technique | Main criteria | | | |
|---|---|---|---|---|
| | MC1-Economic | MC2-Environmental | MC3-Technical | MC4-Socio-economic |
| AHP-GMM | 0.4610 | 0.2450 | 0.1020 | 0.1920 |
| AHP-WAMM | 0.4350 | 0.2290 | 0.0860 | 0.2490 |
| FAHP-WAM1 | 0.2710 | 0.2655 | 0.2113 | 0.2522 |
| FAHP-WAM2 | 0.4991 | 0.2839 | 0.0000 | 0.2170 |
| FAHP-WAM3 | 0.4986 | 0.2912 | 0.0271 | 0.1832 |
| Modified FAHP | 0.4438 | 0.2548 | 0.1189 | 0.1826 |

**Level 3 - Local weights of evaluation criteria**

| Technique | Evaluation criteria | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | EC1-MC1 | EC2-MC1 | EC3-MC1 | EC4-MC1 | EC5-MC2 | EC6-MC2 | EC7-MC3 | EC8-MC3 | EC9-MC4 | EC10-MC4 |
| AHP-GMM | 0.4770 | 0.2550 | 0.1920 | 0.0760 | 0.7620 | 0.2380 | 0.8500 | 0.1500 | 0.4200 | 0.5800 |
| AHP-WAMM | 0.4580 | 0.2460 | 0.2150 | 0.0820 | 0.7150 | 0.2860 | 0.8440 | 0.1560 | 0.4300 | 0.5700 |
| FAHP-WAM1 | 0.3046 | 0.2757 | 0.2690 | 0.1507 | 0.5488 | 0.4512 | 0.7143 | 0.2857 | 0.4911 | 0.5089 |
| FAHP-WAM2 | 0.4603 | 0.3052 | 0.2345 | 0.0000 | 1.0000 | 0.0000 | 1.0000 | 0.0000 | 0.3800 | 0.6200 |
| FAHP-WAM3 | 0.4333 | 0.3073 | 0.2594 | 0.0000 | 1.0000 | 0.0000 | 1.0000 | 0.0000 | 0.3430 | 0.6570 |
| Modified FAHP | 0.4146 | 0.2771 | 0.2245 | 0.0838 | 0.7581 | 0.2419 | 0.8353 | 0.1647 | 0.4326 | 0.5674 |

**Level 3 - Global weights of evaluation criteria[a]**

| Technique | Evaluation criteria | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | EC1-MC1 | EC2-MC1 | EC3-MC1 | EC4-MC1 | EC5-MC2 | EC6-MC2 | EC7-MC3 | EC8-MC3 | EC9-MC4 | EC10-MC4 |
| AHP-GMM | 0.21990 | 0.11756 | 0.08851 | 0.03504 | 0.18669 | 0.05831 | 0.08670 | 0.01530 | 0.08064 | 0.11136 |
| AHP-WAMM | 0.19923 | 0.10701 | 0.09353 | 0.03567 | 0.16374 | 0.06549 | 0.07258 | 0.01342 | 0.10707 | 0.14193 |
| FAHP-WAM1 | 0.08254 | 0.07470 | 0.07288 | 0.04083 | 0.14574 | 0.11980 | 0.15096 | 0.06038 | 0.12384 | 0.12833 |
| FAHP-WAM2 | 0.22975 | 0.15231 | 0.11703 | 0.00000 | 0.28394 | 0.00000 | 0.00000 | 0.00000 | 0.08245 | 0.13452 |
| FAHP-WAM3 | 0.21604 | 0.15319 | 0.12934 | 0.00000 | 0.29118 | 0.00000 | 0.02706 | 0.00000 | 0.06283 | 0.12035 |
| Modified FAHP | 0.18400 | 0.12295 | 0.09964 | 0.03717 | 0.19312 | 0.06163 | 0.09933 | 0.01959 | 0.07897 | 0.10358 |

[a] Global weights of evaluation criteria resulted from the multiplication of local weight of each evaluation criterion by the weight of their main own criterion

**Level 4 - Local priority weights of alternatives (derived for each alternative with respect to all evaluation criteria from EC1-MC1 to EC10-MC4); evaluation criteria herein indicated as E1 to E10**

| Technique | Alternative Alt.1- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 1-E1 | Alt. 1-E2 | Alt. 1-E3 | Alt. 1-E4 | Alt. 1-E5 | Alt. 1-E6 | Alt. 1-E7 | Alt. 1-E8 | Alt. 1-E9 | Alt. 1-E10 |
| AHP-GMM | 0.17740 | 0.12320 | 0.10110 | 0.08920 | 0.06640 | 0.04960 | 0.06710 | 0.06270 | 0.09550 | 0.07800 |
| AHP-WAMM | 0.17080 | 0.11980 | 0.10350 | 0.09900 | 0.07650 | 0.05730 | 0.08600 | 0.07900 | 0.09600 | 0.08450 |
| FAHP-WAM1 | 0.10997 | 0.10463 | 0.10343 | 0.10394 | 0.10039 | 0.09285 | 0.10294 | 0.10257 | 0.10157 | 0.10247 |
| FAHP-WAM2 | 0.14091 | 0.12038 | 0.11258 | 0.10775 | 0.09148 | 0.05720 | 0.09328 | 0.09104 | 0.10061 | 0.08869 |
| FAHP-WAM3 | 0.13779 | 0.11501 | 0.11139 | 0.09862 | 0.08092 | 0.04807 | 0.07527 | 0.07728 | 0.10223 | 0.07836 |
| Modified FAHP | 0.14816 | 0.11083 | 0.10254 | 0.09140 | 0.07537 | 0.05472 | 0.07260 | 0.06992 | 0.09553 | 0.07538 |

| Technique | Alternative Alt.2- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 2-E1 | Alt. 2-E2 | Alt. 2-E3 | Alt. 2-E4 | Alt. 2-E5 | Alt. 2-E6 | Alt. 2-E7 | Alt. 2-E8 | Alt. 2-E9 | Alt. 2-E10 |
| AHP-GMM | 0.13300 | 0.11000 | 0.07700 | 0.05000 | 0.02500 | 0.05400 | 0.02900 | 0.03200 | 0.13400 | 0.05500 |
| AHP-WAMM | 0.14100 | 0.12400 | 0.09200 | 0.07500 | 0.02400 | 0.07500 | 0.02900 | 0.03200 | 0.13700 | 0.05400 |
| FAHP-WAM1 | 0.10949 | 0.10374 | 0.10234 | 0.10020 | 0.06490 | 0.09850 | 0.06112 | 0.07086 | 0.10730 | 0.09654 |
| FAHP-WAM2 | 0.13803 | 0.12082 | 0.10305 | 0.07930 | 0.00000 | 0.07299 | 0.01870 | 0.02530 | 0.12453 | 0.08187 |
| FAHP-WAM3 | 0.13264 | 0.11979 | 0.09056 | 0.05651 | 0.00000 | 0.05403 | 0.00726 | 0.02320 | 0.12912 | 0.07520 |
| Modified FAHP | 0.13437 | 0.11484 | 0.08296 | 0.05608 | 0.02677 | 0.05800 | 0.03664 | 0.03748 | 0.13044 | 0.06750 |

| Technique | Alternative Alt.3- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 3-E1 | Alt. 3-E2 | Alt. 3-E3 | Alt. 3-E4 | Alt. 3-E5 | Alt. 3-E6 | Alt. 3-E7 | Alt. 3-E8 | Alt. 3-E9 | Alt. 3-E10 |
| AHP-GMM | 0.15100 | 0.15200 | 0.17000 | 0.11000 | 0.13900 | 0.12900 | 0.20900 | 0.18500 | 0.17200 | 0.15200 |
| AHP-WAMM | 0.16300 | 0.14000 | 0.15600 | 0.10600 | 0.13500 | 0.12000 | 0.19700 | 0.17300 | 0.16100 | 0.13900 |
| FAHP-WAM1 | 0.11164 | 0.10727 | 0.10775 | 0.10374 | 0.11007 | 0.10595 | 0.12299 | 0.11616 | 0.10939 | 0.11213 |
| FAHP-WAM2 | 0.14803 | 0.13723 | 0.14640 | 0.11794 | 0.13261 | 0.13002 | 0.16001 | 0.14364 | 0.13222 | 0.14028 |
| FAHP-WAM3 | 0.13662 | 0.14924 | 0.15659 | 0.12410 | 0.13614 | 0.13695 | 0.17657 | 0.15045 | 0.14186 | 0.14456 |
| Modified FAHP | 0.14364 | 0.14506 | 0.15764 | 0.11725 | 0.12654 | 0.12493 | 0.17765 | 0.15794 | 0.15235 | 0.14163 |

| Technique | Alternative Alt.4- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 4-E1 | Alt. 4-E2 | Alt. 4-E3 | Alt. 4-E4 | Alt. 4-E5 | Alt. 4-E6 | Alt. 4-E7 | Alt. 4-E8 | Alt. 4-E9 | Alt. 4-E10 |
| AHP-GMM | 0.14600 | 0.16100 | 0.18200 | 0.14500 | 0.17100 | 0.15400 | 0.10600 | 0.13400 | 0.14700 | 0.11500 |
| AHP-WAMM | 0.13400 | 0.14400 | 0.16500 | 0.13100 | 0.16300 | 0.14100 | 0.10900 | 0.12900 | 0.13500 | 0.10200 |
| FAHP-WAM1 | 0.10966 | 0.11013 | 0.10853 | 0.10697 | 0.11431 | 0.10923 | 0.11290 | 0.10826 | 0.10765 | 0.10611 |
| FAHP-WAM2 | 0.13775 | 0.14368 | 0.15152 | 0.13022 | 0.15006 | 0.14341 | 0.12039 | 0.12737 | 0.12526 | 0.11944 |
| FAHP-WAM3 | 0.13661 | 0.15398 | 0.16108 | 0.13696 | 0.15796 | 0.15377 | 0.11653 | 0.12856 | 0.13204 | 0.12425 |
| Modified FAHP | 0.14306 | 0.15878 | 0.16238 | 0.13506 | 0.16070 | 0.14690 | 0.10707 | 0.12399 | 0.13470 | 0.11485 |

| Technique | Alternative Alt.5- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 5-E1 | Alt. 5-E2 | Alt. 5-E3 | Alt. 5-E4 | Alt. 5-E5 | Alt. 5-E6 | Alt. 5-E7 | Alt. 5-E8 | Alt. 5-E9 | Alt. 5-E10 |
| AHP-GMM | 0.07200 | 0.11400 | 0.09600 | 0.20300 | 0.16300 | 0.15600 | 0.18600 | 0.14500 | 0.10400 | 0.16800 |
| AHP-WAMM | 0.07800 | 0.12500 | 0.11500 | 0.19000 | 0.16200 | 0.15000 | 0.17700 | 0.14700 | 0.10800 | 0.16200 |
| FAHP-WAM1 | 0.10116 | 0.10617 | 0.10460 | 0.11038 | 0.11420 | 0.10979 | 0.12040 | 0.11430 | 0.10465 | 0.11462 |
| FAHP-WAM2 | 0.10052 | 0.12605 | 0.11866 | 0.15108 | 0.14955 | 0.14750 | 0.15287 | 0.13711 | 0.11447 | 0.14755 |
| FAHP-WAM3 | 0.09444 | 0.14177 | 0.10613 | 0.16091 | 0.15522 | 0.16161 | 0.16864 | 0.14021 | 0.11346 | 0.15139 |
| Modified FAHP | 0.08153 | 0.12227 | 0.09706 | 0.17575 | 0.15680 | 0.15925 | 0.16714 | 0.14212 | 0.10952 | 0.15357 |

| Technique | Alternative Alt.6- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 6-E1 | Alt. 6-E2 | Alt. 6-E3 | Alt. 6-E4 | Alt. 6-E5 | Alt. 6-E6 | Alt. 6-E7 | Alt. 6-E8 | Alt. 6-E9 | Alt. 6-E10 |
| AHP-GMM | 0.13900 | 0.11200 | 0.09800 | 0.13900 | 0.08700 | 0.09200 | 0.10800 | 0.12200 | 0.12000 | 0.10200 |
| AHP-WAMM | 0.13200 | 0.11300 | 0.09300 | 0.13000 | 0.09200 | 0.09400 | 0.10600 | 0.11900 | 0.12200 | 0.11300 |
| FAHP-WAM1 | 0.10918 | 0.10529 | 0.10278 | 0.10621 | 0.10365 | 0.09997 | 0.11032 | 0.10896 | 0.10639 | 0.11119 |
| FAHP-WAM2 | 0.13727 | 0.11894 | 0.11067 | 0.12867 | 0.10885 | 0.10460 | 0.11684 | 0.11966 | 0.12044 | 0.12601 |
| FAHP-WAM3 | 0.13509 | 0.12146 | 0.10967 | 0.13837 | 0.10768 | 0.10817 | 0.11812 | 0.12202 | 0.12398 | 0.12386 |
| Modified FAHP | 0.14271 | 0.10596 | 0.10252 | 0.13550 | 0.09770 | 0.09604 | 0.10445 | 0.11386 | 0.12351 | 0.11451 |

| Technique | Alternative Alt.7- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 7-E1 | Alt. 7-E2 | Alt. 7-E3 | Alt. 7-E4 | Alt. 7-E5 | Alt. 7-E6 | Alt. 7-E7 | Alt. 7-E8 | Alt. 7-E9 | Alt. 7-E10 |
| AHP-GMM | 0.06000 | 0.05300 | 0.06400 | 0.07300 | 0.07400 | 0.08600 | 0.08800 | 0.09200 | 0.07500 | 0.06000 |
| AHP-WAMM | 0.05600 | 0.05100 | 0.05900 | 0.07200 | 0.07500 | 0.08300 | 0.08600 | 0.08600 | 0.07700 | 0.05800 |
| FAHP-WAM1 | 0.09747 | 0.08238 | 0.09371 | 0.09760 | 0.10296 | 0.09963 | 0.10724 | 0.10431 | 0.09873 | 0.09130 |
| FAHP-WAM2 | 0.08295 | 0.04104 | 0.06957 | 0.09088 | 0.10393 | 0.10388 | 0.11182 | 0.10402 | 0.09119 | 0.06363 |
| FAHP-WAM3 | 0.08633 | 0.04367 | 0.08058 | 0.09435 | 0.10018 | 0.11241 | 0.11435 | 0.11076 | 0.08643 | 0.06275 |
| Modified FAHP | 0.07272 | 0.05898 | 0.07526 | 0.08508 | 0.08949 | 0.09954 | 0.10333 | 0.10075 | 0.08038 | 0.06440 |

| Technique | Alternative Alt.8- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 8-E1 | Alt. 8-E2 | Alt. 8-E3 | Alt. 8-E4 | Alt. 8-E5 | Alt. 8-E6 | Alt. 8-E7 | Alt. 8-E8 | Alt. 8-E9 | Alt. 8-E10 |
| AHP-GMM | 0.03600 | 0.03800 | 0.04700 | 0.05000 | 0.05200 | 0.04300 | 0.06800 | 0.06700 | 0.05300 | 0.04900 |
| AHP-WAMM | 0.03400 | 0.03500 | 0.04500 | 0.04700 | 0.05100 | 0.04100 | 0.07000 | 0.07300 | 0.05100 | 0.04400 |
| FAHP-WAM1 | 0.08041 | 0.09086 | 0.08921 | 0.09225 | 0.09012 | 0.08427 | 0.10257 | 0.10280 | 0.08947 | 0.08549 |
| FAHP-WAM2 | 0.03192 | 0.03580 | 0.04331 | 0.06811 | 0.06855 | 0.04726 | 0.10016 | 0.09869 | 0.06650 | 0.05891 |
| FAHP-WAM3 | 0.04626 | 0.02992 | 0.04547 | 0.07086 | 0.06958 | 0.03821 | 0.09568 | 0.08766 | 0.06436 | 0.06833 |
| Modified FAHP | 0.04368 | 0.04278 | 0.05443 | 0.06453 | 0.06441 | 0.05000 | 0.08461 | 0.07931 | 0.06240 | 0.06378 |

| Technique | Alternative Alt.9- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 9-E1 | Alt. 9-E2 | Alt. 9-E3 | Alt. 9-E4 | Alt. 9-E5 | Alt. 9-E6 | Alt. 9-E7 | Alt. 9-E8 | Alt. 9-E9 | Alt. 9-E10 |
| AHP-GMM | 0.05600 | 0.09200 | 0.13100 | 0.11300 | 0.18400 | 0.20200 | 0.11200 | 0.12900 | 0.06700 | 0.18500 |
| AHP-WAMM | 0.06200 | 0.09100 | 0.13500 | 0.12700 | 0.17900 | 0.20300 | 0.11600 | 0.13300 | 0.08100 | 0.21100 |
| FAHP-WAM1 | 0.09944 | 0.10374 | 0.10610 | 0.10576 | 0.11466 | 0.11296 | 0.11290 | 0.11418 | 0.10080 | 0.11939 |
| FAHP-WAM2 | 0.07320 | 0.10879 | 0.13444 | 0.12271 | 0.15143 | 0.16187 | 0.12592 | 0.13583 | 0.09516 | 0.16790 |
| FAHP-WAM3 | 0.06229 | 0.10911 | 0.13660 | 0.11484 | 0.15680 | 0.16778 | 0.12757 | 0.13708 | 0.08224 | 0.15695 |
| Modified FAHP | 0.05652 | 0.09469 | 0.13072 | 0.10960 | 0.15800 | 0.17106 | 0.11770 | 0.13930 | 0.07569 | 0.16714 |

| Technique | Alternative Alt.10- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 10-E1 | Alt. 10-E2 | Alt. 10-E3 | Alt. 10-E4 | Alt. 10-E5 | Alt. 10-E6 | Alt. 10-E7 | Alt. 10-E8 | Alt. 10-E9 | Alt. 10-E10 |
| AHP-GMM | 0.02900 | 0.04500 | 0.03400 | 0.02700 | 0.03900 | 0.03500 | 0.02600 | 0.03100 | 0.03100 | 0.03700 |
| AHP-WAMM | 0.02600 | 0.05700 | 0.03900 | 0.02600 | 0.04200 | 0.03800 | 0.02600 | 0.02900 | 0.03200 | 0.03500 |
| FAHP-WAM1 | 0.07157 | 0.08579 | 0.08155 | 0.07292 | 0.08473 | 0.08686 | 0.04661 | 0.05761 | 0.07406 | 0.06077 |
| FAHP-WAM2 | 0.00943 | 0.04728 | 0.00981 | 0.00335 | 0.04354 | 0.03127 | 0.00000 | 0.01733 | 0.02963 | 0.00571 |
| FAHP-WAM3 | 0.03193 | 0.01605 | 0.00193 | 0.00449 | 0.03552 | 0.01900 | 0.00000 | 0.02277 | 0.02429 | 0.01435 |
| Modified FAHP | 0.03361 | 0.04582 | 0.03450 | 0.02976 | 0.04422 | 0.03958 | 0.02882 | 0.03532 | 0.03548 | 0.03724 |

**Level 4 - Global priority weights of alternatives (derived for each option with respect to all evaluation criteria)[b]**

| Technique | Alternative Alt.1- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 1-E1 | Alt. 1-E2 | Alt. 1-E3 | Alt. 1-E4 | Alt. 1-E5 | Alt. 1-E6 | Alt. 1-E7 | Alt. 1-E8 | Alt. 1-E9 | Alt. 1-E10 |
| AHP-GMM | 0.03901 | 0.01448 | 0.00895 | 0.00313 | 0.01240 | 0.00289 | 0.00582 | 0.00096 | 0.00770 | 0.00869 |
| AHP-WAMM | 0.03403 | 0.01282 | 0.00968 | 0.00353 | 0.01253 | 0.00375 | 0.00624 | 0.00106 | 0.01028 | 0.01199 |
| FAHP-WAM1 | 0.00908 | 0.00782 | 0.00754 | 0.00424 | 0.01463 | 0.01112 | 0.01554 | 0.00619 | 0.01258 | 0.01315 |
| FAHP-WAM2 | 0.03237 | 0.01834 | 0.01318 | 0.00000 | 0.02597 | 0.00000 | 0.00000 | 0.00000 | 0.00830 | 0.01193 |
| FAHP-WAM3 | 0.02977 | 0.01762 | 0.01441 | 0.00000 | 0.02356 | 0.00000 | 0.00204 | 0.00000 | 0.00642 | 0.00943 |
| Modified FAHP | 0.02726 | 0.01363 | 0.01022 | 0.00340 | 0.01456 | 0.00337 | 0.00721 | 0.00137 | 0.00754 | 0.00781 |

| Technique | Alternative Alt.2- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 2-E1 | Alt. 2-E2 | Alt. 2-E3 | Alt. 2-E4 | Alt. 2-E5 | Alt. 2-E6 | Alt. 2-E7 | Alt. 2-E8 | Alt. 2-E9 | Alt. 2-E10 |
| AHP-GMM | 0.02925 | 0.01293 | 0.00682 | 0.00175 | 0.00467 | 0.00315 | 0.00251 | 0.00049 | 0.01081 | 0.00612 |
| AHP-WAMM | 0.02809 | 0.01327 | 0.00860 | 0.00268 | 0.00393 | 0.00491 | 0.00210 | 0.00043 | 0.01467 | 0.00766 |
| FAHP-WAM1 | 0.00904 | 0.00775 | 0.00746 | 0.00409 | 0.00946 | 0.01180 | 0.00923 | 0.00428 | 0.01329 | 0.01239 |
| FAHP-WAM2 | 0.03171 | 0.01840 | 0.01206 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.01027 | 0.01101 |
| FAHP-WAM3 | 0.02866 | 0.01835 | 0.01171 | 0.00000 | 0.00000 | 0.00000 | 0.00020 | 0.00000 | 0.00811 | 0.00905 |
| Modified FAHP | 0.02472 | 0.01412 | 0.00827 | 0.00208 | 0.00517 | 0.00357 | 0.00364 | 0.00073 | 0.01030 | 0.00699 |

| Technique | Alternative Alt.3- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 3-E1 | Alt. 3-E2 | Alt. 3-E3 | Alt. 3-E4 | Alt. 3-E5 | Alt. 3-E6 | Alt. 3-E7 | Alt. 3-E8 | Alt. 3-E9 | Alt. 3-E10 |
| AHP-GMM | 0.03320 | 0.01787 | 0.01505 | 0.00385 | 0.02595 | 0.00752 | 0.01812 | 0.00283 | 0.01387 | 0.01693 |
| AHP-WAMM | 0.03247 | 0.01498 | 0.01459 | 0.00378 | 0.02210 | 0.00786 | 0.01430 | 0.00232 | 0.01724 | 0.01973 |
| FAHP-WAM1 | 0.00921 | 0.00801 | 0.00785 | 0.00424 | 0.01604 | 0.01269 | 0.01857 | 0.00701 | 0.01355 | 0.01439 |
| FAHP-WAM2 | 0.03401 | 0.02090 | 0.01713 | 0.00000 | 0.03765 | 0.00000 | 0.00000 | 0.00000 | 0.01090 | 0.01887 |
| FAHP-WAM3 | 0.02952 | 0.02286 | 0.02025 | 0.00000 | 0.03964 | 0.00000 | 0.00478 | 0.00000 | 0.00891 | 0.01740 |
| Modified FAHP | 0.02643 | 0.01784 | 0.01571 | 0.00436 | 0.02444 | 0.00770 | 0.01765 | 0.00309 | 0.01203 | 0.01467 |

| Technique | Alternative Alt.4- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 4-E1 | Alt. 4-E2 | Alt. 4-E3 | Alt. 4-E4 | Alt. 4-E5 | Alt. 4-E6 | Alt. 4-E7 | Alt. 4-E8 | Alt. 4-E9 | Alt. 4-E10 |
| AHP-GMM | 0.03210 | 0.01893 | 0.01611 | 0.00508 | 0.03192 | 0.00898 | 0.00919 | 0.00205 | 0.01185 | 0.01281 |
| AHP-WAMM | 0.02670 | 0.01541 | 0.01543 | 0.00467 | 0.02669 | 0.00923 | 0.00791 | 0.00173 | 0.01445 | 0.01448 |
| FAHP-WAM1 | 0.00905 | 0.00823 | 0.00791 | 0.00437 | 0.01666 | 0.01309 | 0.01704 | 0.00654 | 0.01333 | 0.01362 |
| FAHP-WAM2 | 0.03165 | 0.02188 | 0.01773 | 0.00000 | 0.04261 | 0.00000 | 0.00000 | 0.00000 | 0.01033 | 0.01607 |
| FAHP-WAM3 | 0.02951 | 0.02359 | 0.02083 | 0.00000 | 0.04599 | 0.00000 | 0.00315 | 0.00000 | 0.00830 | 0.01495 |
| Modified FAHP | 0.02632 | 0.01952 | 0.01618 | 0.00502 | 0.03103 | 0.00905 | 0.01063 | 0.00243 | 0.01064 | 0.01190 |

| Technique | Alternative Alt.5- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 5-E1 | Alt. 5-E2 | Alt. 5-E3 | Alt. 5-E4 | Alt. 5-E5 | Alt. 5-E6 | Alt. 5-E7 | Alt. 5-E8 | Alt. 5-E9 | Alt. 5-E10 |
| AHP-GMM | 0.01583 | 0.01340 | 0.00850 | 0.00711 | 0.03043 | 0.00910 | 0.01613 | 0.00222 | 0.00839 | 0.01871 |
| AHP-WAMM | 0.01554 | 0.01338 | 0.01076 | 0.00678 | 0.02653 | 0.00982 | 0.01285 | 0.00197 | 0.01156 | 0.02299 |
| FAHP-WAM1 | 0.00835 | 0.00793 | 0.00762 | 0.00451 | 0.01664 | 0.01315 | 0.01818 | 0.00690 | 0.01296 | 0.01471 |
| FAHP-WAM2 | 0.02309 | 0.01920 | 0.01389 | 0.00000 | 0.04246 | 0.00000 | 0.00000 | 0.00000 | 0.00944 | 0.01985 |
| FAHP-WAM3 | 0.02040 | 0.02172 | 0.01373 | 0.00000 | 0.04520 | 0.00000 | 0.00456 | 0.00000 | 0.00713 | 0.01822 |
| Modified FAHP | 0.01500 | 0.01503 | 0.00967 | 0.00653 | 0.03028 | 0.00981 | 0.01660 | 0.00278 | 0.00865 | 0.01591 |

| Technique | Alternative Alt.6- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 6-E1 | Alt. 6-E2 | Alt. 6-E3 | Alt. 6-E4 | Alt. 6-E5 | Alt. 6-E6 | Alt. 6-E7 | Alt. 6-E8 | Alt. 6-E9 | Alt. 6-E10 |
| AHP-GMM | 0.03057 | 0.01317 | 0.00867 | 0.00487 | 0.01624 | 0.00536 | 0.00936 | 0.00187 | 0.00968 | 0.01136 |
| AHP-WAMM | 0.02630 | 0.01209 | 0.00870 | 0.00464 | 0.01506 | 0.00616 | 0.00769 | 0.00160 | 0.01306 | 0.01604 |
| FAHP-WAM1 | 0.00901 | 0.00786 | 0.00749 | 0.00434 | 0.01511 | 0.01198 | 0.01665 | 0.00658 | 0.01317 | 0.01427 |
| FAHP-WAM2 | 0.03154 | 0.01812 | 0.01295 | 0.00000 | 0.03091 | 0.00000 | 0.00000 | 0.00000 | 0.00993 | 0.01695 |
| FAHP-WAM3 | 0.02919 | 0.01861 | 0.01419 | 0.00000 | 0.03136 | 0.00000 | 0.00320 | 0.00000 | 0.00779 | 0.01491 |
| Modified FAHP | 0.02626 | 0.01303 | 0.01022 | 0.00504 | 0.01887 | 0.00592 | 0.01038 | 0.00223 | 0.00975 | 0.01186 |

| Technique | Alternative Alt.7- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 7-E1 | Alt. 7-E2 | Alt. 7-E3 | Alt. 7-E4 | Alt. 7-E5 | Alt. 7-E6 | Alt. 7-E7 | Alt. 7-E8 | Alt. 7-E9 | Alt. 7-E10 |
| AHP-GMM | 0.01319 | 0.00623 | 0.00566 | 0.00256 | 0.01382 | 0.00501 | 0.00763 | 0.00141 | 0.00605 | 0.00668 |
| AHP-WAMM | 0.01116 | 0.00546 | 0.00552 | 0.00257 | 0.01228 | 0.00544 | 0.00624 | 0.00115 | 0.00824 | 0.00823 |
| FAHP-WAM1 | 0.00805 | 0.00615 | 0.00683 | 0.00399 | 0.01501 | 0.01193 | 0.01619 | 0.00630 | 0.01223 | 0.01172 |
| FAHP-WAM2 | 0.01906 | 0.00625 | 0.00814 | 0.00000 | 0.02951 | 0.00000 | 0.00000 | 0.00000 | 0.00752 | 0.00856 |
| FAHP-WAM3 | 0.01865 | 0.00669 | 0.01042 | 0.00000 | 0.02917 | 0.00000 | 0.00309 | 0.00000 | 0.00543 | 0.00755 |
| Modified FAHP | 0.01338 | 0.00725 | 0.00750 | 0.00316 | 0.01728 | 0.00613 | 0.01026 | 0.00197 | 0.00635 | 0.00667 |

| Technique | Alternative Alt.8- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 8-E1 | Alt. 8-E2 | Alt. 8-E3 | Alt. 8-E4 | Alt. 8-E5 | Alt. 8-E6 | Alt. 8-E7 | Alt. 8-E8 | Alt. 8-E9 | Alt. 8-E10 |
| AHP-GMM | 0.00792 | 0.00447 | 0.00416 | 0.00175 | 0.00971 | 0.00251 | 0.00590 | 0.00103 | 0.00427 | 0.00546 |
| AHP-WAMM | 0.00677 | 0.00375 | 0.00421 | 0.00168 | 0.00835 | 0.00269 | 0.00508 | 0.00098 | 0.00546 | 0.00624 |
| FAHP-WAM1 | 0.00664 | 0.00679 | 0.00650 | 0.00377 | 0.01313 | 0.01009 | 0.01548 | 0.00621 | 0.01108 | 0.01097 |
| FAHP-WAM2 | 0.00733 | 0.00545 | 0.00507 | 0.00000 | 0.01946 | 0.00000 | 0.00000 | 0.00000 | 0.00548 | 0.00792 |
| FAHP-WAM3 | 0.00999 | 0.00458 | 0.00588 | 0.00000 | 0.02026 | 0.00000 | 0.00259 | 0.00000 | 0.00404 | 0.00822 |
| Modified FAHP | 0.00804 | 0.00526 | 0.00542 | 0.00240 | 0.01244 | 0.00308 | 0.00840 | 0.00155 | 0.00493 | 0.00661 |

| Technique | Alternative Alt.9- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 9-E1 | Alt. 9-E2 | Alt. 9-E3 | Alt. 9-E4 | Alt. 9-E5 | Alt. 9-E6 | Alt. 9-E7 | Alt. 9-E8 | Alt. 9-E9 | Alt. 9-E10 |
| AHP-GMM | 0.01231 | 0.01082 | 0.01160 | 0.00396 | 0.03435 | 0.01178 | 0.00971 | 0.00197 | 0.00540 | 0.02060 |
| AHP-WAMM | 0.01235 | 0.00974 | 0.01263 | 0.00453 | 0.02931 | 0.01330 | 0.00842 | 0.00178 | 0.00867 | 0.02995 |
| FAHP-WAM1 | 0.00821 | 0.00775 | 0.00773 | 0.00432 | 0.01671 | 0.01353 | 0.01704 | 0.00689 | 0.01248 | 0.01532 |
| FAHP-WAM2 | 0.01682 | 0.01657 | 0.01573 | 0.00000 | 0.04300 | 0.00000 | 0.00000 | 0.00000 | 0.00785 | 0.02259 |
| FAHP-WAM3 | 0.01346 | 0.01671 | 0.01767 | 0.00000 | 0.04566 | 0.00000 | 0.00345 | 0.00000 | 0.00517 | 0.01889 |
| Modified FAHP | 0.01040 | 0.01164 | 0.01303 | 0.00407 | 0.03051 | 0.01054 | 0.01169 | 0.00273 | 0.00598 | 0.01731 |

| Technique | Alternative Alt.1- (EC1-MC1 (E1) to EC10 –MC4 (E10)) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt. 10-E1 | Alt. 10-E2 | Alt. 10-E3 | Alt. 10-E4 | Alt. 10-E5 | Alt. 10-E6 | Alt. 10-E7 | Alt. 10-E8 | Alt. 10-E9 | Alt. 10-E10 |
| AHP-GMM | 0.00638 | 0.00529 | 0.00301 | 0.00095 | 0.00728 | 0.00204 | 0.00225 | 0.00047 | 0.00250 | 0.00412 |
| AHP-WAMM | 0.00518 | 0.00610 | 0.00365 | 0.00093 | 0.00688 | 0.00249 | 0.00189 | 0.00039 | 0.00343 | 0.00497 |
| FAHP-WAM1 | 0.00591 | 0.00641 | 0.00594 | 0.00298 | 0.01235 | 0.01041 | 0.00704 | 0.00348 | 0.00917 | 0.00780 |
| FAHP-WAM2 | 0.00217 | 0.00720 | 0.00115 | 0.00000 | 0.01236 | 0.00000 | 0.00000 | 0.00000 | 0.00244 | 0.00077 |
| FAHP-WAM3 | 0.00690 | 0.00246 | 0.00025 | 0.00000 | 0.01034 | 0.00000 | 0.00000 | 0.00000 | 0.00153 | 0.00173 |
| Modified FAHP | 0.00618 | 0.00563 | 0.00344 | 0.00111 | 0.00854 | 0.00244 | 0.00286 | 0.00069 | 0.00280 | 0.00386 |

[b] **Global priority weights of alternatives resulted from the multiplication of local priority weight for each alternative with the global weights of evaluation criteria**

**Total priority weights of alternatives**[c]

| Technique | Alternatives | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alt.1 | Alt. 2 | Alt. 3 | Alt. 4 | Alt. 5 | Alt. 6 | Alt. 7 | Alt. 8 | Alt. 9 | Alt. 10 |
| AHP-GMM | 0.10402 | 0.07850 | 0.15519 | 0.14903 | 0.12981 | 0.11115 | 0.06824 | 0.04716 | 0.12250 | 0.03429 |
| AHP-WAMM | 0.10591 | 0.08635 | 0.14938 | 0.13671 | 0.13217 | 0.11134 | 0.06629 | 0.04521 | 0.13067 | 0.03589 |
| FAHP-WAM1 | 0.10189 | 0.08878 | 0.11157 | 0.10983 | 0.11095 | 0.10646 | 0.09839 | 0.09066 | 0.10999 | 0.07148 |
| FAHP-WAM2 | 0.11008 | 0.08345 | 0.13947 | 0.14027 | 0.12793 | 0.12039 | 0.07904 | 0.05072 | 0.12255 | 0.02609 |
| FAHP-WAM3 | 0.10325 | 0.07608 | 0.14336 | 0.14633 | 0.13096 | 0.11923 | 0.08101 | 0.05558 | 0.12101 | 0.02320 |
| Modified FAHP | 0.09636 | 0.07961 | 0.14391 | 0.14273 | 0.13028 | 0.11355 | 0.07997 | 0.05813 | 0.11791 | 0.03755 |

[c] **Total priority weights of alternatives resulted from the summation of their global priority weights with respect to all evaluation criteria**

## Appendix G

Sensitivity analysis outcomes for FAHP-WAM1; FAHP-WAM2 and FAHP-WAM3 techniques (changes in priority order ranking of alternatives in association with changes in priority weights of main criteria, each in turn, for a sensitivity interval ranging from 0 to 1)

- Sensitivity analysis for FAHP-WAM1

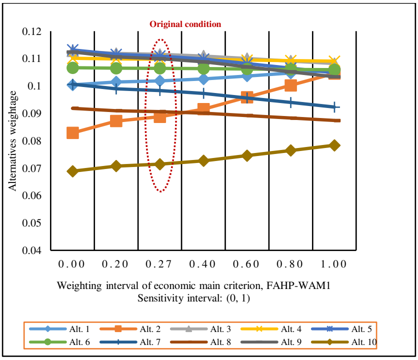


Figure G.1

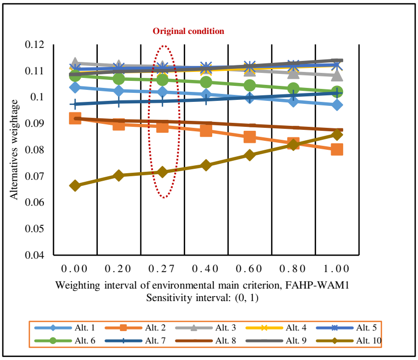


Figure G.2

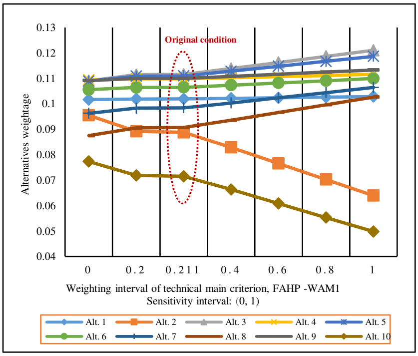


Figure G.3

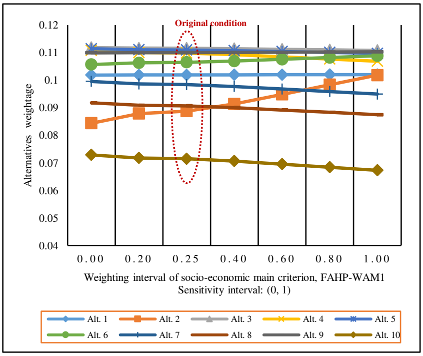


Figure G.4

- Sensitivity analysis for FAHP-WAM2

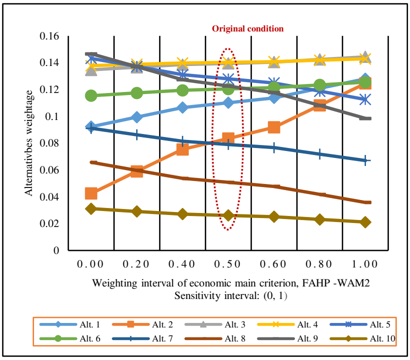


Figure G.5

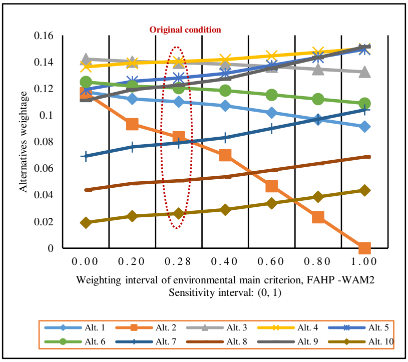


Figure G.6

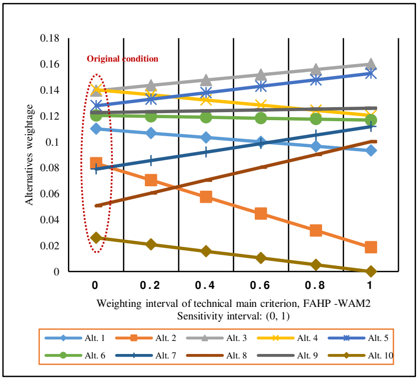


Figure G.7

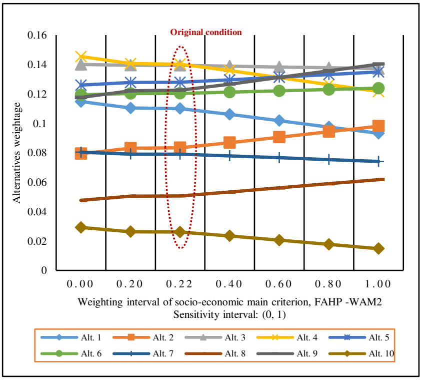


Figure G.8

- Sensitivity analysis for FAHP-WAM3

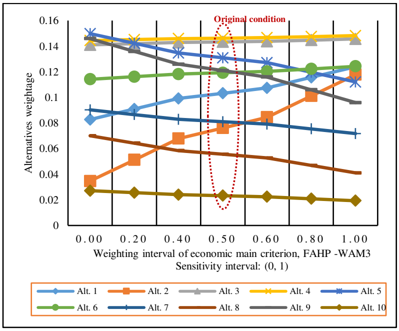


**Figure G.9**

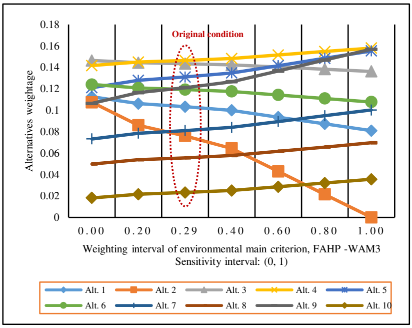


**Figure G.10**

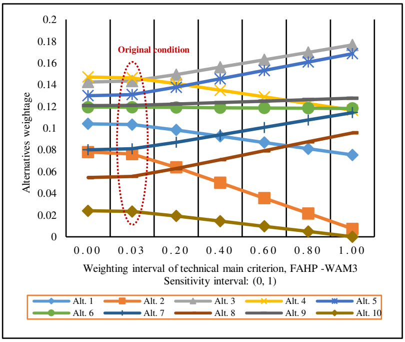


**Figure G.11**

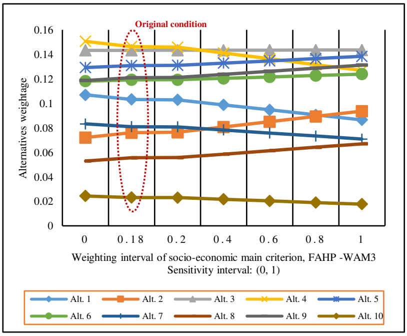


**Figure G.12**

# List of published and/or submitted papers

**Parts of this thesis have been published and/or submitted for publication in the following papers:**


1- **Zyoud Sh.**, Shaheen H., Samhan S., Rabi A., Al-Wadi F., Fuchs-Hanusch D. (2016). Utilizing analytic hierarchy process (AHP) for decsision making in water loss management of intermittent water supply systems. Journal of Water, Saniation and Hygiene for Developemnt, 6(4), 534-546. DOI: 10.2166/washdev.2016.123

2- **Zyoud Sh.** & Fuchs-Hanusch D. (2017). Comparison of several multi criteria decision making (MCDM) techniques: A case of water loss management in developing countries. Water Resources Mangement (Under review).

3- **Zyoud Sh.**, Kaufman L., Shaheen H., Samhan S., Fuchs-Hanusch D. (2016). A framework for water loss management in developing countries under fuzzy environment: Integration of Fuzzy AHP with Fuzzy TOPSIS. Expert Systems With Applications, 61, 86-105. http://doi.org/10.1016/j.eswa.2016.05.016

4- **Zyoud Sh.** & Fuchs-Hanusch D. (2017). A bibliometric-based survey on AHP and TOPSIS techniques. Expert Systems With Applications, 78, 158-181. http://doi.org/10.1016/j.eswa.2017.02.016

## Mitteilungen des Institutes für Wasserwirtschaft und Konstruktiven Wasserbau der Technischen Universität Graz

**Bisher erschienene Hefte:**

| | | | |
|---|---|---|---|
| Heft | 1 | (1959) | VEDER, C.: Neue Verfahren zur Herstellung von untertägigen Wänden und Injektionsschirmen in Lockergesteinen und durchlässigem Fels (vergriffen) |
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