# Strategic Planning for Water Loss Reduction with Imprecise Data

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## Abstract

Water utilities particularly in the developing countries continue to operate with considerable inefficiencies in terms of water and revenue losses. With increasing water demand and scarcity, utilities require effective strategies for optimum use of available water resources. Often the information needed for strategic planning is inadequate and decisions have to be made on the basis of limited and uncertain data. Whereas decision-makers endeavour to obtain accurate and reliable data, they are often hindered or frustrated by the cost and time needed to collect the data. In this paper, an integrated multi-criteria decision-aiding framework for strategic planning of water loss management is presented. The PROMETHEE II method was applied within the framework in prioritizing water loss reduction options for Kampala city, Uganda. A strategic plan that combines selective mains and service lines replacement and pressure management as priorities is the best compromise based on preferences of the decision makers and seven evaluation criteria characterized by financial-economic, environmental, public health, technical and social impacts. The results show that the most preferred options are those that enhance water supply reliability, public health and water conservation measures. This study demonstrates that even without sufficient resources to generate precise data, utilities in developing countries can still use appropriate tools to plan and prioritize water loss reduction options.

***Keywords:*** Multi-criteria decision analysis; Strategic planning; Water loss reduction.

## Introduction

Water utilities around the world are still facing challenges of high water losses despite the tools and methodologies developed in the last two decades to help reduce the losses. According to the World Bank study, about 48 billion m$^3$ of water is lost annually from water distribution systems (WDSs) costing water utilities about US$ 14 billion per year around the world (Kingdom et al. 2006). In Asian cities, non-revenue water (NRW) expressed as a percentage of total water supply ranges from 4.4% (PUB, Singapore) to 63.8% (Maynilad, Manila) (ADB 2010). In Africa NRW figures ranging from 5% (Saldanha Bay, South Africa) to 70% (LWSC, Liberia) have been reported (WSP 2009). In Latin American water utilities, NRW averages 40% (Corton and Berg 2007). High levels of water losses are indicative of poor governance and poor physical conditions of the WDSs (Male et al. 1985; McIntosh 2003). Water losses not only have economic and environment dimensions but also public health and social impacts. Leakage, often leads to service interruption, is costly in terms of energy losses and may cause water quality contamination via pathogen intrusion (Cabrera et al. 2010; Karim et al. 2003). With global pressures of climate change, rapid urbanization, increasing water demand and water scarcity, utilities require effective strategies to conserve water resources and ensure sustainable delivery of water services.

Strategic planning (SP) has proven to be a valuable tool for sustainable urban water management (Malmqvist et al. 2006). However, water utilities in developing countries often lack the necessary capabilities to carryout SP (Mugabi et al. 2007). SP is about setting a long-term direction based on sound predictions, analysis of options and key decisions about the future of an organisation. The Uganda National Water and Sewerage Corporation (NWSC) corporate plan (2009-2012) broadly categorises water loss reduction among other sub-goals under the main goal of revenue maximization (NWSC 2009a). This traditional way of strategic planning based on a single economic criterion of maximising revenue is unrealistic as water loss is a multiple-criteria problem that is better solved using discrete multi-criteria decision analysis (MCDA) techniques.

MCDA is a tool developed in the field of decision theory for resolving operational research (OR) problems with a finite number of decision options based on a set of evaluation criteria that are often non-commensurate and conflicting (Figueira et al. 2005). MCDA techniques have been widely used in the water resources domain including water demand management (Cabrera Jr et al. 2011) and water treament (Bouchard et al. 2010). However, its application to water loss management (WLM) has been limited. Morais and Almeida (2007), developed a leakage strategy for a water utility in Brazil applying group decision making and the PROMETHEE (Preference Ranking and Organization Method for Enrichment Evaluation) outranking method of the MCDA family. Although Morais and Almeida (2007) addressed leakage strategy in WDS, they did not tackle water loss in totality as the apparent water loss component that is often significant in developing countries was not considered. In addition, they did not carry out a water balance to identify whether the problem was leakage or apparent losses. They instead indicate a water loss of 60% for the case study. It is well known that use of percentage as a water loss indicator can be misleading as it is heavily influenced by consumption and has nothing to do with water loss control (Fanner et al. 2007).

In this paper, an integrated MCDA framework for strategic water loss management planning (SWLMP) is proposed to aid urban water utility decision-makers (DMs) in evaluating and prioritising water loss reduction strategies. The framework methodology is applied to a typical developing country city of Kampala, Uganda in East Africa. For the case study water supply system, seven evaluation criteria (EC) under five main objectives that take into account the sustainability triple bottom line approach (economic, enviromental and social) were identified and examined. The framework uses the PROMETHEE method that is able to work with both quantitative and qualitative data. This is particulary useful for developing countries where knowledge of the impact of the alternative water loss reduction options is relatively scarce and often predicted with high uncertainty.

## The MCDA Integrated Methodology Framework

This section elaborates on an integrated MCDA group decision-aiding framework for SWLMP in water utilities. The proposed decision-aiding framework is shown in Figure 1. Due to size limitations of this paper, the MCDA decision-making process and the PROMETHEE method used in the integrated framework are not fully described here. For more details, the reader is refered to Mutikanga *et al*. (2011b).

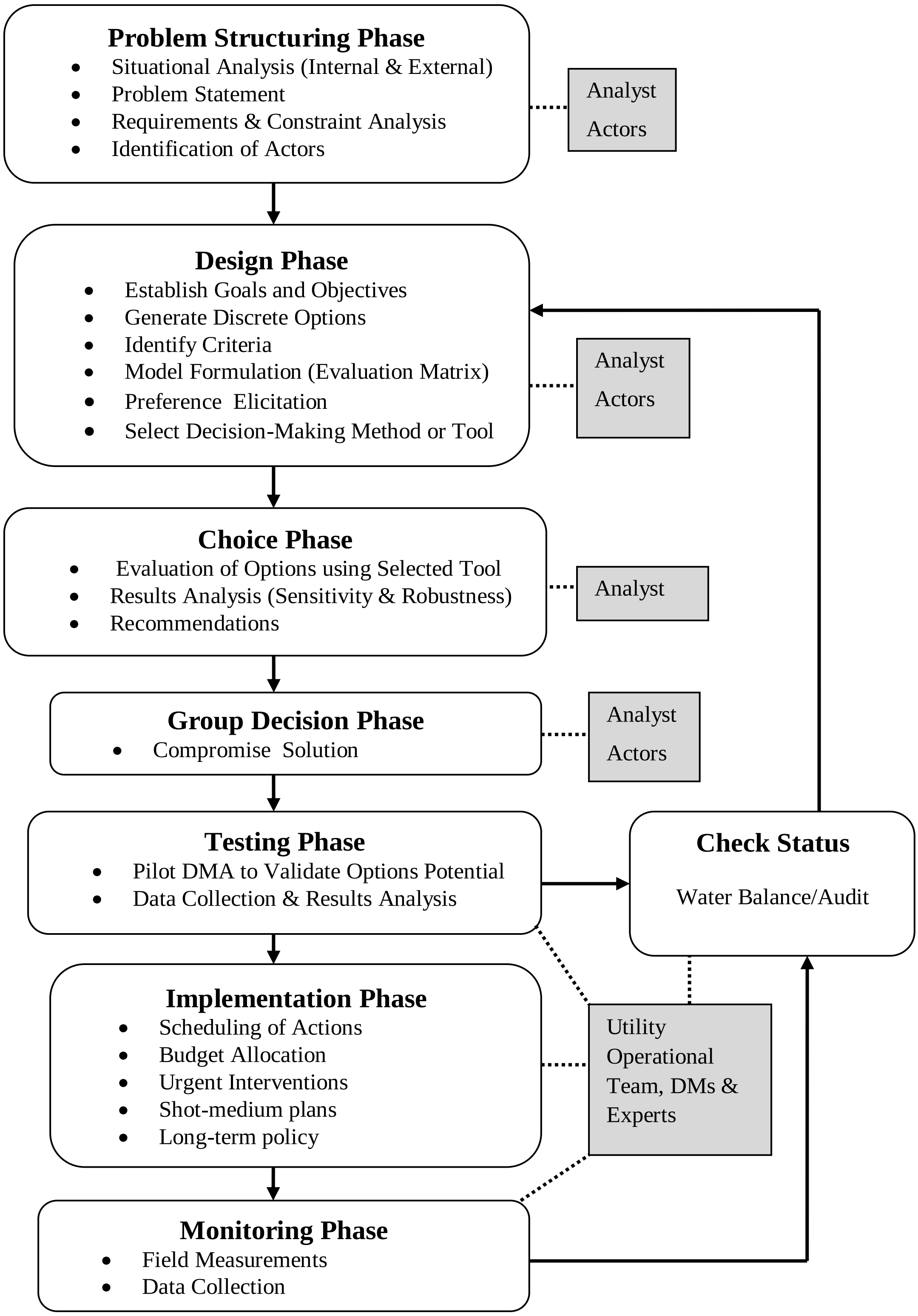


**Figure 1.** Multi-criteria Decision-aiding Framework for SWLMP

**Application to the KWDS Case Study**

The framework methodology was applied to the NWSC's Kampala Water Distribution System (KWDS) in Uganda's capital city of Kampala. The KWDS service area encompasses an area of about 350 $km^2$ with an estimated population of 1.5 million and 73% water coverage. Water supply has not kept pace with population growth with consequences of irregular supply in most parts of the city. The development of the KWDS commenced in the year 1928 and water production has since been gradually increasing up to the current average level of about 148,000 $m^3$/day, serving about 150,000 service connections. The condition of the network has deteriorated over the years, due to poor operating practices and inadequate strategic asset management (Mutikanga et al. 2009). The major customer complaints are related to supply interruptions and low pressure as a result of frequent mains bursts and service line leakages. The average number of failures reported during the year 2010 was 1175 breaks/100 km/year. Pipeline systems having an average annual pipe break ratio per 100 km of less than 40 are considered to be in an acceptable state (Pelletier et al. 2003). Apparent losses are also high with rampant illegal use of water, high metering inaccuracies and meter failure. NRW averages about 43% of system input volume or 22 million $m^3$ per year (NWSC 2009b).

*Problem formulation for the KWDS*

Based on the case study information the agreed upon problem statement was documented as "*identify and prioritize strategies to reduce water losses in KWDS*".

*Requirements*

The problem definition dictated the following key requirements for the decision problem:

1. Strategy options should address both real and apparent losses.
2. Cost of implementing a set of selected strategies should not exceed €3.6 million per year.
3. Strategies should lead to a water loss reduction of at least 12 million $m^3$ per year.
4. Implementation period to achieve water loss reduction target should not exceed 10 years.

*Actors:* The actors (DMs, users, and other stakeholders) were proposed by the analyst and approved by the General Manger of Kampala Water utility. Three actor groups were identified to represent utility DMs, water users and environmentalists. In total eight DMs were selected for the preference elicitation process. In this study, actors are referred to as the eight DMs (DM1 to DM8).

*Establishing goals and objectives*: The goals and objectives of the study were derived from the utility's mission of "*providing safe and reliable water services to customers at a fair price and in an environmentally friendly manner*". The goal of this study was to reduce water losses in the KWDS. The goals were viewed in the broader national water sector policy of utility financial viability, environmental protection, public health protection, technically acceptable level of service and socio-economic aspects. In light of the aforementioned, the following five main objectives were established: (i) maximize revenues and minimize costs, (ii) maximize water savings, (iii) maximize good quality water, (iv) maximize water supply reliability, and (v) maximize affordability of water.

*Generating options*: In order to generate appropriate water loss reduction strategy options, a water balance was established by the utility water loss department using the IWA/AWWA water balance methodology (AWWA 2009) and the proposed methodology for assessing the apparent loss component (Mutikanga et al. 2011a). The water balance for KWDS is shown in Table 1.

**Table 1** KWDS Water Balance for year 2010

| Parameter | Water Loss Components | Unit | Quantity | Error Margin (95% confidence level) |
|---|---|---|---|---|
| System Input Volume | | $m^3$ | 52,499,787 | ±7.0% |
| Revenue Water | | $m^3$ | 30,891,487 | |
| Non-Revenue Water | | $m^3$ | 21,608,300 | ±15.3% |
| Water Losses | | $m^3$ | 21,319,631 | ±7.9% |
| | Real Losses | $m^3$ | 11,863,566 | ±7.5% |
| | Apparent Losses | $m^3$ | 9,456,065 | ±2.5% |
| | Customer Metering Errors | $m^3$ | 8,726,065 | ±1.0% |
| | Unauthorised Consumption | $m^3$ | 730,000 | ±2.3% |

Based on the KWDS water balance (Table 1), the following seven strategy options were proposed by the analyst and accepted by the DMs: (i) meter replacement (S1), (ii) illegal use control (S2), (iii) improved speed and quality of repairs (S3), (iv) selective mains and service line replacements (S4), (v) network zoning and establishing District Meter Areas (DMAs) (S5), (vi) pressure management (S6), and (vii) active leakage control (S7).

The strategy options were selected from a rich menu developed by the International Water Association (IWA) and the American Water Works Association (AWWA) based on many years of research (Alegre et al. 2006; AWWA 2009; Fanner et al. 2007). The options address both real and apparent losses as they are both significant.

*Determining evaluation criteria*

The evaluation criteria (EC) are measures of performance by which the strategy options are judged. A brain-storming session with actors was arranged to derive the criteria relevant for performance evaluation. The objectives and criteria decision-making hierarchy is presented in Figure 2. Due to insufficient performance evaluation data and to avoid “black box” effects, not all criteria (Figure 2) were used in the decision process although it was important to highlight and discuss all potential EC with the stakeholders. Out of the 15 criteria (Figure 2), only seven key criteria (Table 2) were selected to assess performance of the alternative strategy options. These criteria are as follows:

1. Revenue generation (EC1).
2. Investment cost (EC2).
3. Operation and maintenance costs (EC3).
4. Water saved (EC4).
5. Water quality (EC5).
6. Supply reliability (EC6).
7. Affordability (EC7).

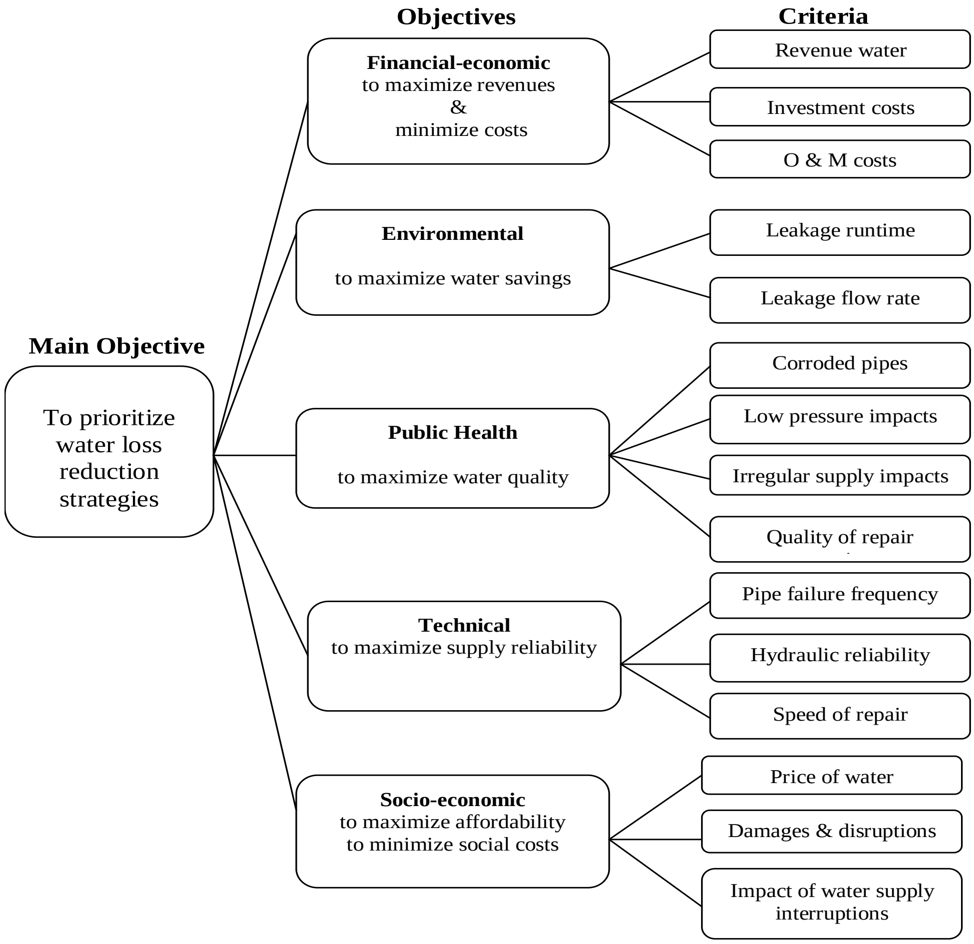


**Figure 2.** Objective Tree Hierarchy of the MCDA Problem

**Table 2.** Evaluation criteria

| Code | Criteria | Description |
|---|---|---|
| EC1 | Revenue generation | The ability of option to improve revenue. The higher the potential, the most preferable the option |
| EC2 | Investment cost | The cost needed to implement the option. The lower the cost, the most preferable the option |
| EC3 | Operation & maintenance costs | The costs associated with adopting the option. The lower the cost, the most preferable the option |
| EC4 | Water saved | The ability of option to reduce leakage. The higher the potential, the most preferable the option |
| EC5 | Water quality | The ability of option to improve water quality. The higher the potential, the most preferable the option |
| EC6 | Supply reliability | The ability of option to minimize supply interruptions. The fewer the frequency of bursts and leaks, the most preferable the option |
| EC7 | Affordability | The impact of option on water tariff. The lower the impact on tariff, the most preferable the option |

*Predicting performance*: The qualitative scores (performance of each option in relation to a criterion) of the evaluation matrix (EM) were provided by experts from the utility's water loss control department. However, predicting the performance of strategy options with certainty is not straightforward. A Likert Scale ranging from 1 (poor performance) to 5 (very good performance) was used to evaluate the qualitative scores and the results are shown in the EM Table 3. This being an interval scale, the intervals between statements are meaningful but scale scores have no meaning.

*Selecting the multi-criteria method* : The MCDA method used was the PROMETHEE II and its D-Sight software tool. There is increasing popularity in solving complex decision problems using PROMETHEE (Behzadian et al. 2010) and its poweful D-sight software (Bernardini et al. 2010). The method is highly appreciated by end-users because it is easy to use, intuitive, auditable, and transparent with several graphical and interactive tools.

*Preference modeling*: The preference elicitation process in the case study comprised of an interviewer-assisted questionnaire survey to derive preference functions (PFs) and weights for the evaluation criteria (EC) and objectives. A survey was conducted on eight DMs and weights were assigned for each criterion and objective to reflect their relative importance to the decision problem. As the criteria were qualitative, the PF applied in this study was the type I (usual criterion) of the six generalized criteria as defined by the authors of the PROMETHEE method (Brans and Mareschal 2005) and in line with guidelines for using the PROMETHEE method (De Keyser and Peeters 1996). The preference thresholds can be chosen by means of the D-Sight software. In this way, a lot of flexibility is provided to represent the preferences of DMs.

**Table 3.** Evaluation matrix

| Objective | | | | Strategy Options | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Criteria | Direction | S1 | S2 | S3 | S4 | S5 | S6 | S7 |
| **Finacial-economic** | | | | | | | | | | |
| | EC1 | Revenue | Maximise | 5 | 3 | 3 | 3 | 1 | 2 | 1 |
| | EC2 | Investment Cost | Minimise | 2 | 1 | 1 | 5 | 3 | 3 | 2 |
| | EC3 | O & M Costs | Minimise | 1 | 4 | 5 | 1 | 2 | 2 | 4 |
| **Environmental** | | | | | | | | | | |
| | EC4 | Water Saved | Maximise | 1 | 1 | 4 | 5 | 2 | 4 | 3 |
| **Public Health** | | | | | | | | | | |
| | EC5 | Water Quality | Maximise | 1 | 1 | 2 | 5 | 2 | 4 | 3 |
| **Technical (Level of Service)** | | | | | | | | | | |
| | EC6 | Supply Reliability | Maximise | 1 | 1 | 3 | 5 | 2 | 4 | 3 |
| **Socio-economic** | | | | | | | | | | |
| | EC7 | Affordability | Maximise | 5 | 4 | 1 | 2 | 2 | 3 | 2 |

*Determining criteria weights*: The weights were derived using the "Revised Simos" Procedure (Figueira and Roy 2002) and the criteria weight values are presented in Table 5. For the group decision, the median was considered as the representative value since it agrees with the majority view of the group. The most important evaluation criterion for prioritising water loss reduction option is water supply reliability (EC6) with the highest average weight of 29%.

**Table 4.** Evaluation criteria weights assigned by each DM

| Criteria | Weight Values | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | DM1 | DM2 | DM3 | DM4 | DM5 | DM6 | DM7 | DM8 | Mean | Median |
| C1 | 19 | 12 | 6 | 18 | 0 | 4 | 15 | 11 | 11 | 12 |
| C2 | 5 | 11 | 7 | 5 | 9 | 0 | 2 | 9 | 6 | 6 |
| C3 | 10 | 8 | 7 | 10 | 4 | 0 | 9 | 9 | 7 | 9 |
| C4 | 26 | 25 | 14 | 33 | 7 | 15 | 12 | 14 | 18 | 15 |
| C5 | 13 | 14 | 16 | 7 | 26 | 15 | 15 | 14 | 15 | 15 |
| C6 | 19 | 20 | 32 | 20 | 35 | 38 | 40 | 24 | 29 | 28 |
| C7 | 7 | 10 | 8 | 7 | 19 | 27 | 8 | 19 | 13 | 9 |

## Results and Discussion

### *Evaluating options*

The water loss reduction strategy options were evaluated and prioritized with the D-Sight Software tool, which uses the PROMETHEE algorithm. The PROMETHEE II individual decision and group decision rankings are shown in Table 5 and Figure 3. The most preferred strategy options are S4 and S6 with scores of 0.64 and 0.36 respectively.

**Table 5.** PROMETHEE II rankings for individual DMs and group scenario

| Rank | Individual Decision Maker | | | | | | | | Group Decision |
|---|---|---|---|---|---|---|---|---|---|
| | DM1 | DM2 | DM3 | DM4 | DM5 | DM6 | DM7 | DM8 | |
| Rank1 | **S4** | **S4** | **S4** | **S4** | **S4** | **S4** | **S4** | **S4** | **S4** |
| Rank2 | **S6** | **S6** | **S6** | **S6** | **S6** | **S6** | **S6** | **S6** | **S6** |
| Rank3 | S3 | S3 | S3 | S3 | S7 | S7 | S3 | S1 | S3 |
| Rank4 | S1 | S7 | S7 | S1 | S3 | S3 | S7 | S3 | S7 |
| Rank5 | S7 | S1 | S5 | S7 | S5 | S1 | S1 | S7 | S1 |
| Rank6 | S5 | S2 | S1 | S5 | S1 | S5 | S5 | S2 | S5 |
| Rank7 | S2 | S5 | S2 | S2 | S2 | S2 | S2 | S5 | S2 |

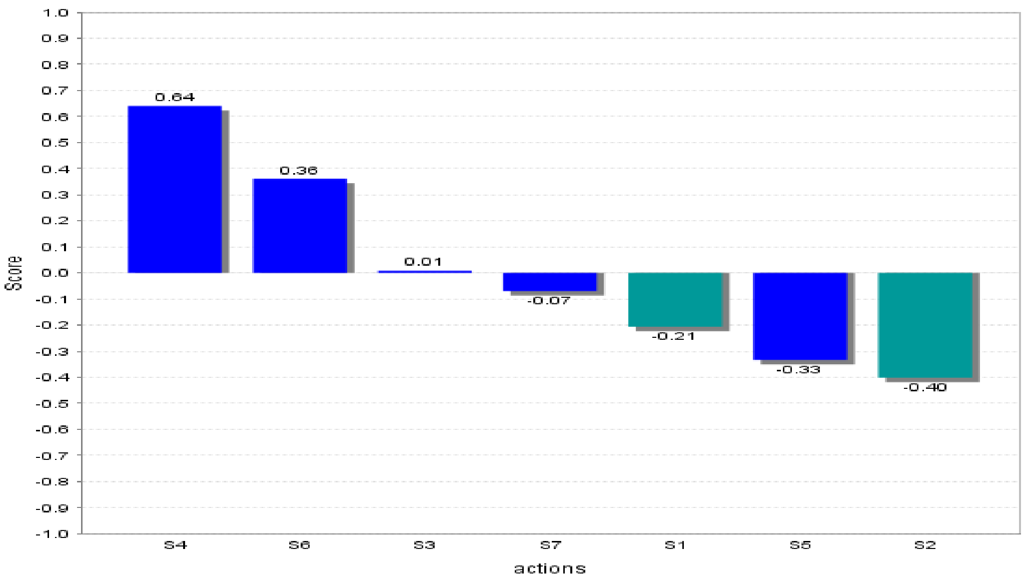


**Figure 3.** PROMETHEE II rankings based on net preference flow (Φ)

Although derived scientifically (Figure 3), the strategic water loss reduction framework for Kampala is in agreement with general guidelines for selecting the order of implementing real loss reduction strategies (Fanner et al. 2007; Trow and Farley 2004).

*Group decision-making phase*: The PROMETHEE and GAIA plane provide both descriptive and prescriptive tools and were exploited during a group meeting organized to discuss the PROMETHEE II ranking of options, sensitivity of weighting criteria and agree on a compromise solution as no alternative is the best one on each criterion. Reaching consensus was rather easy as there was no dispute on the first two best options (S4 and S6) and minor disagreements on the third ranked option (S3) and last option (S2) as shown in Table 5. The reasons for the prioritised ranking according to the DMs were as follows:

- Leaking pipes increase energy costs, erode utility revenue and compromise quality of service leading to serious operational problems. Mains and service lines replacement do not only reduce leakage but also improve system hydraulic reliability and water quality.
- Pressure management (PM) is the only tool that can proactively control leakage once pipes have been laid. In addition, PM reduces main break frequency and extends useful life of infrastructure among other benefits.
- Imporved speed and quality of repair is the only strategy that repairs actual failures and will always be used to supplement other strategies.
- Active leakage control emerged low due to the fact that there is no sense in putting too much effort in detecting invisible underground leaks in a city like Kampala where the utility is overwhelmed by visible leaks.
- Network zoning and DMA establishment: this is a complementary strategy to other strategies to enable leakage assessment and leak detection.
- Meter replacements and illegal use control were ranked so low based on the urgument that reliable water supply of good quality and adequate pressure must first be available before it is stolen and measured accurately.

*Sensitivity Analysis*: The sensitivity of the results was analyzed using the capabilities of the D-Sight Software in-built tools. The results are presented in Table 6. The stability intervals indicate the range in which the weight of a criterion can be changed without affecting the ranking. For example, the technical criterion with an initial normalized weight of 30.4% may be weighted between 19.7% and 44.7% (stability interval of 25%) without affecting the ranking provided all other factors remain constant. The sensitivity of the ranking can be considered as marginal with respect to the criteria weight values assigned.

**Table 6.** Weight sensitivity analysis of group on strategy ranking

| Criteria | Min. Weight | Value | Max. Weight | Stability Interval |
|---|---|---|---|---|
| Financial-economic | 19.5% | 28.3% | 35.4% | 15.9% |
| Environmental | 2.7% | 15.8% | 33.0% | 30.3% |
| Public Health | 6.3% | 15.8% | 27.1% | 20.8% |
| Technical | 19.7% | 30.4% | 44.7% | 25.0% |
| Social-economic | 0.2% | 9.8% | 15.4% | 15.2% |

## Conclusions

This study presented an integrated MCDA strategic planning framework methodology for evaluating and prioritizing water loss reduction options. The framework explicitly considers seven evaluation criteria within five main sustainability dimensions of economic, environmental, technical and social objectives. The framework includes the PROMETHEE outranking method with its D-Sight software tool in solving the decision problem. The MCDA integrated framework allows for participatory decision making in which stakeholder preferences are elicited and explicitly incorporated into the decision process. Results indicate that water supply reliability has the highest influence on prioritizing water loss reduction options (29%); followed by water savings (15.8%) and water quality (15.8%). Conversely, the criterion with the lowest influence is the investment cost (6%). For KWDS, the prioritized options for water loss reduction were mains and service lines replacement followed by pressure management and improved speed and quality of repairs. The results demonstrate that the cheapest option is not necessarily the best when multiple-criteria are considered in an explicit way. Sensitivity analysis shows the stability of the ranking with the least stability interval of 15.2% for affordability.

It is envisaged that the integrated MCDA framework methodology will be a valuable planning tool for water utility managers particularly in developing countries where the problem of water loss is more prominent and accurate prediction of the performance of strategy options is constrained by often insufficient and imprecise data. The methodology is generic and can easily accommodate additional options and criteria, making its adaptation to other water utilities very easy.

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