Journal of Water Supply: Research and Technology—AQUA | 59.4 | 2010

Multicriteria decision analysis for the selection of a small drinking water treatment system

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ABSTRACT

The selection of a small drinking water treatment system for a hydro-electrical plant is addressed within a multicriteria and participatory decision analysis process. As a first step, based on problem constraints, we identified and retained three water treatment systems alternatives. In close collaboration with the stakeholders, we then defined and obtained weights for criteria that take into account public health, costs, system impacts and perception issues. The ELECTRE II method was used to aggregate the alternatives evaluations in order to obtain a ranking of the three water treatment systems. The process revealed that the system which combines NF and UV disinfection is ranked first for all the different stakeholder weightings. The sensitivity analysis of the aggregation parameters and evaluations reinforced that conclusion. This study provides useful information for conducting similar analysis on industrial or municipal water treatment systems.

Key words | decision analysis, decision making, drinking water, multicriteria, small systems, water treatment

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INTRODUCTION

The selection of a drinking water treatment system is a problem of increasing complexity due to the tightening of water standards, growing consumer concerns and the diversification of treatment technologies. Although the basis on which decisions are made may vary greatly, this selection process should nonetheless take explicitly into account, not only cost considerations, but also technical, financial and social aspects, particularly for small systems in areas where qualified human resources are limited.

The problem that is addressed in this paper is the selection of a drinking water treatment system that will supply drinking water to workers and visitors in a remote hydro-electric plant in Québec, Canada. This is a semi-structured problem, where quantifiable factors such as costs exhibit uncertainties and where human or social factors are difficult to quantify. Some parameters, like quality standards, are susceptible to change during the lifespan of the facility, adding to the uncertainty. Such a complex decision-making process would clearly benefit from a systematic, rigorous and transparent approach to criteria modelling and alternatives evaluation (Keeney & McDaniels 2000; Bond *et al.* 2008). We were therefore motivated to conduct our project in a participatory multicriteria (also known as multiobjective or multiple objective decision making) decision analysis (MCDA) framework involving various stakeholders. In doing so, we adopted the point of view of Bana e Costa *et al.* (1997), where the use of several criteria is a more robust approach to multidimensional and semi-structured problems than the traditional one-dimensional approach (such as cost-benefit analysis), facilitating the

doi: 10.2166/aqua.2010.071

learning and thinking of the stakeholders about their problem and their own values and preferences.

The objective of this paper is to perform an MCDA for the selection of a water treatment system by simultaneously considering relevant technical and non-technical dimensions. In the course of our analysis, we took into account dimensions including public health, treatment reliability and robustness, investment and operations costs, availability of qualified human and technical resources, impact and perception issues, ease of operation and adaptability. We favoured a participatory approach that included many stakeholders.

This paper is organized as follows. First the methodology is presented, namely the decision analysis process followed, which includes the construction of the alternatives set and the evaluation criteria. Then, the multicriteria aggregation method used, ELECTRE II, is described along with the evaluations, the results and the sensitivity analysis, followed by a conclusion.

METHODS

MCDA has been applied in a variety of water-related problems. Hajkowicz & Collins (2007), in their review of 113 published water management MCDA studies from 34 countries, found that MCDA is heavily used for water policy evaluation, strategic planning and infrastructure selection. Its use is motivated by the desire to ensure that the decision processes are transparent, rigorous and auditable where a decision must be made in a context of multiple, conflicting and non-commensurable criteria. Very few applications of MCDA to drinking water treatment technology selection have been published. Chowdhury & Husain (2006) applied fuzzy sets to take into account uncertainties in their MCDA of disinfection processes. Their approach is based on the Analytic Hierarchy Process developed by Saaty (1990). deMonsabert *et al.* (2003) used multiobjective decision analysis to evaluate disinfection processes for a drinking water treatment facility in Virginia, USA. They used an additive value function model to obtain the final alternatives ranking.

Although the problem we face is a selection problem, we addressed it as a ranking problem where our goal was to rank the alternatives from best to worst with a possibility of alternatives being of equal rank or even incomparable. Figure 1 illustrates the decision analysis process that we followed.

We initiated our project by analysing the human and physical environment with a special emphasis on the structure of the organization responsible for installing and operating the water treatment system. We started by reviewing the current decision-making process followed

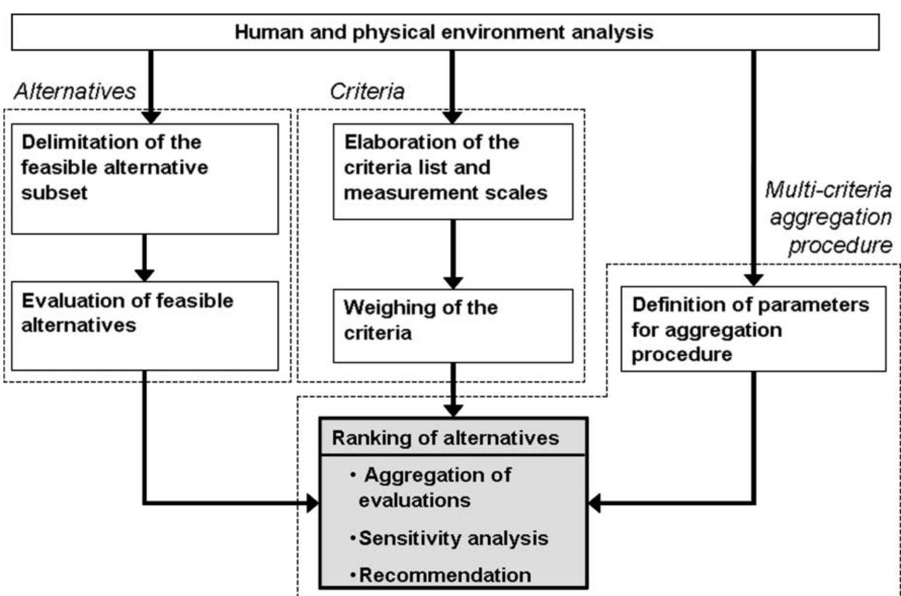


Figure 1 | The decision analysis process.

within the organization from the time a decision is made to carry out a technical project, through the design phase and all the way to the physical implementation phase of the project. We then identified and interacted with the different stakeholders to understand the way they work, their expectations and concerns regarding the project. Our participative approach gathered nine internal stakeholders' representatives including engineers and managers involved in technological choices, technicians, maintenance staff, as well as environmental and health officers. Three stakeholders external to the organization, who are water treatment specialists, were also identified and asked to participate in different steps of the process. As for the researchers who conducted this study, we played the role of experts in our respective fields, namely water treatment or decision analysis. We completed our first analysis phase by an initial visit to the future water treatment facility site.

In our opinion, this analysis of the physical environment phase greatly facilitated the criteria definition phase. We believe that skipping the physical environment analysis, particularly the social and human aspects, is a potential mistake as it may lead to the blind application of a technology that is not adapted to the situation, in particular for small systems where human resources are limited.

Subsequently, we conducted four main tasks, described in detail in the following sections, namely:

- the definition of the treatment alternatives set;
- the definition of criteria and the evaluation of the alternatives;
- the choice of a multicriteria aggregation procedure and its application to rank the alternatives based on preference information from internal stakeholders;
- the sensitivity analysis of the results.

Definition of the alternatives set

The water treatment alternatives that we analysed in order to design feasible alternatives consist of sequences of unit operations that allow the production of drinking water from raw water. We took into account the following constraints:

- Raw water quality;
- Standards for drinking water quality, including mandatory treatment processes and desirable aesthetic properties;
- Physical and environmental constraints on the size and operation mode of the system;
- Operator skills and operator training capacity.

In our case, the raw water source of the treatment facility is a dam reservoir of the Côte Nord region of the Province of Québec, Canada. Groundwater was not a feasible source option in this case since the hydroelectric plants are located on the slope of mountains that are rocky. The raw water is a coloured surface water (20 to 40 TCU) with a dissolved organic carbon, DOC, ranging from 4.3 to 7.2 mg/L It has a very low alkalinity (below 10 mg $CaCO_3$/L) and mineral content (conductivity below 20 μS/cm). Its microbiological contamination is also low with an average annual faecal coliform count below 5 CFU/100 mL. Its turbidity is low as well (less than 1.2 NTU 95% of the time; 1.3 NTU maximum). The SUVA (UV absorbance at 254 nm/DOC) is higher than 3.4 L/(m cm) indicating the predominance of humic substances in the natural organic matter, which is typical of lake waters in the Canadian Shield (a broad region of Precambrian rock that encircles Hudson Bay in Canada). This high humic substance content is coherent with a high potential for trihalomethanes (THMs) formation as observed following a chlorination simulation we conducted within this project (simulated distribution system THMs of 120 to 280 μg/L; incubation conditions: 24 h, 10°C, final residual chlorine = 0.5 mg/L, initial pH = 6).

The *Regulation respecting the quality of drinking water* of the Province of Québec (Government of Québec 2001) prescribes mandatory filtration and disinfection of surface water as well as turbidity standards, requirements for eliminating pathogens and quality standards for organic and inorganic contaminants. Based on the microbiological contamination level of the raw water, the pathogen removal or inactivation requirements are 4 log for viruses, 3 log for *Giardia* and 2 log for *Cryptosporidium* (Government of Québec 2001, 2002). Because of the potential for THM formation (chlorination by-products) and the colour aesthetic objective, natural organic matter (NOM) has to be partly removed. Secondary disinfection is not mandatory since the distribution network is located inside the plant and not underground, thereby reducing the risk of pathogen intrusion in the network. The design flow rate ranges from 10 to 20 m^3/d, which corresponds to very low flow rates.

The visit to the facility site revealed that the upcoming water treatment systems have to be set up in limited spaces. This eliminated the possibility of extensive water treatment such as slow sand filtration. It also revealed that the hydroelectric plants are very confined spaces where the use of toxic volatile substances and gases must be kept at a minimum because of the prohibitive cost of the necessary adequate ventilation. This constraint eliminated the possibility of using ozone and chlorine dioxide. Double disinfection (chlorination and UV) was never considered as an option because of the high level of THM precursors in the raw water, because it would not significantly reduce water colour and because UV disinfection was not allowed on water with low UV transmittance (<60%).

The existing water treatment systems in the power plants are operated by mechanics technicians who are responsible for higher priority tasks than water treatment monitoring, and who have minimal water treatment background. The potential for training these technicians is limited to a few days per year. We therefore discarded processes requiring coagulation since the monitoring of such processes is relatively complex, especially for low alkalinity raw water and cold water that may need delicate coagulant and coagulant aid dosing adjustments.

Based on the above constraints, the following primary disinfection processes were retained as possible alternatives:

- Chlorination (inactivation of viruses and *Giardia* cysts) after the removal of THM precursors;
- UV irradiation (inactivation of viruses, *Giardia* cysts and *Cryptosporidium* oocysts) after adequate increase of water transmittance;
- Nanofiltration (NF) (removal of *Giardia* cysts and *Cryptosporidium* oocysts).

Furthermore, ion exchange (IE) and NF were retained as possible NOM removal processes. These processes are recommended by the Government of Québec for the removal of NOM in the case of small systems and coloured surface water (Ellis 2009). Tubular NF (USEPA 2000) was chosen because it is a fairly easy system to operate. It has large tangential flow channels resulting in minimal blocking and allows for the mechanical cleaning of the membrane surface with small sponge balls. This reduces the chemical cleaning frequency of the membrane to only a few per year. Based on the above constraints and the commercially available processes, three treatment alternatives were retained and subsequently evaluated based on the criteria defined in the next section (Figure 2):

- NFUV: removal of NOM with tubular NF and primary disinfection with UV (*Giardia*, *Cryptosporidium*, viruses);
- NFCL: removal of NOM and partial disinfection (*Giardia*, *Cryptosporidium*) with tubular NF, and complementary disinfection with chlorination (viruses);
- IEUV: multimedia pre-filtration, NOM removal by anionic IE, post-filtration with cartridge filters and primary disinfection with UV (*Giardia*, *Cryptosporidium*, viruses).

It is worth mentioning that for the NFUV alternative, no membrane integrity monitoring is required, except permeate turbidity monitoring. For the NFCL alternative a daily membrane integrity monitoring (tracer test in this case) is mandatory to be granted disinfection log credits. For the three alternatives, the raw water must be pre-filtered

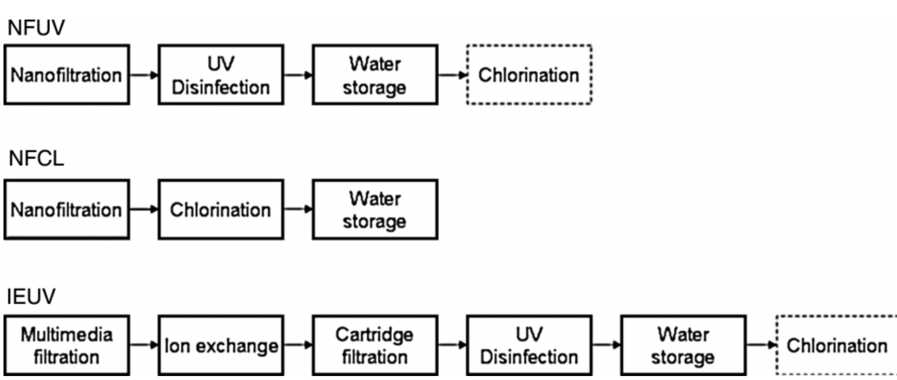


Figure 2 | Water treatment alternatives (dotted line: emergency chlorination).

(75 μm) before treatment. As for the treatment's performance, and based on pilot and full-scale existing systems, the treated water turbidity remains below 0.03 NTU for NFUV and NFCL and below 0.7 NTU for IEUV (95th percentiles). DOC reduction is around 90% for NFUV and NFCL, and ranges from 60 to 80% for IEUV. Credited removal/inactivation rates for viruses, *Giardia* cysts and *Cryptosporidium* oocysts are respectively 4 log, 3 log and 3 log, both for NFUV and IEUV, whereas those rates are ≥10 log, ≥3.7 log and 3 log for NFCL. The investment costs are respectively 300 K$, 310 K$ and 260 K$ for the NFUV, NFCL and IEUV systems. The annual operation and maintenance costs are respectively 10 K$, 62 K$ and 63 K$ for the NFUV, NFCL and IEUV options. All these costs are based on similar existing facilities.

Definition of the criteria

One of the main goals of our study was to move from a single criterion approach based solely on financial considerations to a multicriteria approach that takes into account the various dimensions of the decision problem. Nonetheless, defining a coherent, operational and exhaustive set of criteria is not an easy task. We used the 'top-down' approach of Keeney (1992). This approach consists of refining the main objective into lower-level objectives, and so on down to the fundamental objectives along the important dimensions. Criteria are then defined to measure the degree to which an alternative attains an objective. The dimensions we considered are similar to Chowdhury & Husain (2006), who retained 16 criteria based on human health risk, availability, management, efficiency and costs of treatment technology, and to deMonsabert *et al.* (2003), who based their study on seven criteria namely minimization of cost, of THM formation, of operator complexity and maximization of proven technology, of regulatory compliance and of maintainability and reliability.

Our overall objective was 'To meet the present and future needs of the employees in terms of drinking water'. This overall objective was broken into four major objectives:

- Maximize water consumer health protection and water supply reliability;
- Minimize water production costs;
- Minimize water treatment system impacts;
- Maximize system acceptance.

As shown in Table 1, these four objectives were divided into nine sub-objectives (denoted by two-digit numbers, for example 1.1) corresponding to fundamental objectives. Furthermore, the sub-objectives 1.1, 1.2, 1.3 and 3.1 were divided into components. For example, sub-objective 1.1 has six components (components of a sub-objective are denoted by three-digit numbers, for example, 1.1.1. A component is a sub-sub-objective).

Major objective 1 was elaborated in the perspective of minimizing the system failure risks. Under 'normal conditions', the three water treatment system alternatives have the proven capacity to provide safe drinking water, i.e. treated water that meets governmental standards. 'Normal conditions' are the conditions that are considered during the design and certification of the system. These pertain to the raw water quality and its variations, and to the operating conditions (hydraulic loading, temperature, etc.). However, actual conditions may be abnormal and the water treatment system alternatives may differ by the:

- likelihood of inducing abnormal operating conditions, which depends on the reliability and ease of operation of the system;
- likelihood of failure under abnormal operating conditions, which depends on the robustness of the system and the operation safety margins with respect to the treatment objectives;
- severity and duration of potential failures, which depend on the robustness and safety margins but also on the ease and speed of failure diagnosis and system repair.

Major objective 2 is rather standard. However, in addition to the conventional investment and operation costs, the cost for potential system upgrading is taken into account. Major objective 3 is about minimizing the impacts of the water treatment system. This includes impacts on operators during monitoring, maintenance and repair activities. Initially, a sub-objective about environmental impacts was considered. It was not retained because energy consumption is not a significant issue in this hydroelectric plant (the energy consumptions are approximately 1 kWh/m^3 for NFCL, 1.15 kWh/m^3 for NFUV and less

Table 1 | Objectives, criteria and evaluation methods

Objective, Sub-objective (Criterion)	Sub-criterion (sub-criterion weight)	Evaluation mode
1. Maximize consumer health protection and water supply reliability		
1.1 Minimize the occurrence of abnormal conditions (Reliability and ease of operation)	1.1.1 Number of critical components (10%) 1.1.2 Quality control of critical components (20%) 1.1.3 Other items reinforcing reliability (10%) 1.1.4 Number of operations (15%) 1.1.5 Complexity of operations (30%) 1.1.6 Complexity of special maintenance (15%)	Subjective quantitative evaluations from available technical data about each sub-system.
1.2 In case of abnormal conditions, minimize the system failure risks in terms of water quality and water quantity (System robustness and safety margins vs. standards)	1.2.1 Robustness vs. viruses removal/inact. (10%) 1.2.2 Robustness vs. *Giardia* removal/inact. (10%) 1.2.3 Robustness vs. *Crypto*. removal/inact. (10%) 1.2.4 Robustness vs. THM formation (10%) 1.2.5 Robustness vs. turbidity removal (5%) 1.2.6 Robustness vs. water supply (15%)	Subjective quantitative evaluations from each sub-system analysis; the number of barriers to pathogens (for crit. 1.2.1, 1.2.2 & 1.2.3) have been considered; simplified fault trees have been built.
	1.2.7 Safety margin vs. viruses removal/inact. (9%) 1.2.8 Safety margin vs. *Giardia* removal/inact. (9%) 1.2.9 Safety margin vs. *Crypto*. removal/inact. (9%) 1.2.10 Safety margin vs. THM formation (9%) 1.2.11 Safety margin vs. turbidity removal (5%)	Subjective quantitative evaluations from water quality standards and expected treated water quality (pilot test study, monitoring campaigns, *Ct* estimations, literature review).
1.3 Minimize the recovery time after a system failure (Ease and speed of failure diagnosis and repair)	1.3.1 Frequency of integrity system monitoring (35%) 1.3.2 Number of data to diagnose a system failure (10%) 1.3.3 Complexity to diagnose a system failure (15%) 1.3.4 Availability of extra pieces of equipment (10%) 1.3.5 Risk of short-term obsolescence of equipments (10%) 1.3.6 Ease of repair without external assistance (10%) 1.3.7 Availability of technical support (10%)	Subjective quantitative evaluations from past experience and available technical and commercial data.
2. Minimize costs		
2.1 Minimize investments (Investments)		Evaluation from quotations and real costs of similar treatment facilities
2.2 Minimize operation costs (Operation costs under normal operating conditions)		Evaluation from quotations and past experience with similar equipments; NF membranes, UV lamps and EI resins replacement costs are considered
2.3 Minimize cost for potential system upgrading (Costs for potential system upgrading)		Subjective quantitative evaluations of economical impacts of different scenarios of regulation strengthening
3. Minimize system impacts		
3.1 Maximize operator health and safety (Operator health and safety)	3.1.1 Chemical risks (40%)	Subjective quantitative evaluation from the nature and frequency of use of chemicals
	3.1.2 Mechanical risks (20%)	Subjective quantitative evaluation based on the equipment characteristics

Table 1 | (*continued*)

Objective, Sub-objective (Criterion)	Sub-criterion (sub-criterion weight)	Evaluation mode
	3.1.3 Noise risks (10%)	Subjective quantitative evaluation based on the equipment characteristics
	3.1.4 Heavy loads risks (30%)	Subjective quantitative evaluation based on analysis of the maintenance operations
4. Maximize system acceptance		
4.1 Maximize technology acceptance (Technology perception by the internal stakeholders)		Survey
4.2 Maximize water quality acceptance (Water quality perception by consumers)		Survey

than 0.25 kWh/m^3 for IEUV). Actually, conducting a life cycle analysis (LCA) on each water treatment system would be the proper way to globally measure environmental impacts of each alternative (Vince *et al.* 2008). However, it was beyond the scope of this study. Major objective 4 takes into account the acceptance/perception dimension of the future users. Water consumers are very sensitive to the aesthetic quality of drinking water; as a matter of fact, it is their main concern. The perception of the reliability of a technology by engineers and operators is also important for its successful implementation.

We therefore defined nine criteria (1.1 to 4.2 in Table 1) to measure the degree to which each sub-objective is attained. Sub-criteria were associated to components where applicable (sub-objectives 1.1, 1.2, 1.3 and 3.1). Criteria and sub-criteria were assessed on a unique constructed performance scale ranging from 1 to 5 defined as follows:

- Very weak (worst performance according to the criterion or sub-criterion) = 1
- Weak = 2
- Average = 3
- Strong = 4
- Very strong (best performance according to the criterion or sub-criterion) = 5

All the objectives and criteria were validated by the nine internal stakeholders (one manager, two engineers, one chief technician, three technicians, one health officer and one environmental adviser), who acted as experts, and by the three external experts (engineers). They all commented on the relevance, clarity and evaluation approach for the criteria.

Criteria weights

The internal experts were asked to provide the relative importance weights of the nine criteria. It appears that these weights significantly depend on the responsibilities and concerns of the internal stakeholders (Figure 3). For the sake of analysis, we only retained four aggregated sets of weights, including a set of average weights, to investigate the robustness of the alternatives ranking.

In order to evaluate the alternatives versus criteria 1.1, 1.2, 1.3 and 3.1, sub-weights were necessary. These weights

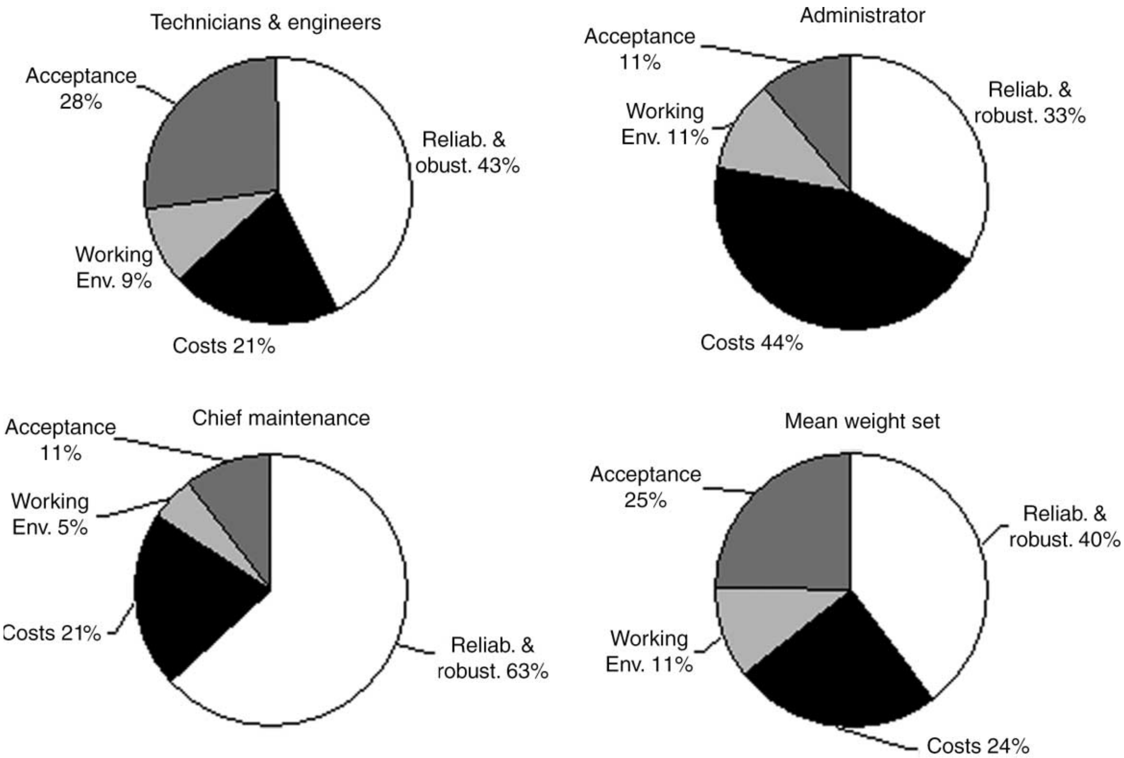


Figure 3 | Sets of criteria weights.

were suggested by the research team and reviewed by the principal engineer (PE) of the project. They are presented in brackets in Table 1.

The evaluations of the alternatives

The evaluations of the three alternatives were performed by the research team in close collaboration with the PE. The evaluation methods, either quantitative or qualitative, are shown in Table 1. It is worth noticing that the evaluation process generated a lot of useful technical information which is an important outcome of this kind of study.

The evaluations are based on data collected from equipment suppliers, on interviews with engineers and operators, on extensive technical and scientific literature review and on the experience of the PE and research team. It is not possible to report all the data that supported those evaluations in the present paper (Bouchard & Beauchamp 2006). However, the approaches that were followed are described below. Some examples are also given.

The evaluation of reliability and ease of operation is based on information about each water treatment subsystem (NF modules, UV reactor, chlorination unit, cartridge filters, IE beds, etc.). For example, the chlorine dosing pump is a critical part of the chlorination unit. The membranes and gaskets are critical parts of the NF modules. The membranes are very thin pieces of material. Therefore, they are considered fragile. The dosing pump is considered much less fragile. The maintenance of the NFUV system is considered moderately complex because of membrane cleaning whereas maintenance of the IEUV system is considered simple.

The evaluation of the robustness of an alternative takes into account the number and robustness of each sub-system that acts as a barrier to water contaminants. This led us to perform simplified fault tree analysis, i.e. develop diagrams that qualitatively show the main failure paths. This is very helpful in identifying the dependency between the different barriers to contaminants. For example, membrane modules tolerate raw water quality degradation because they are physical barriers but their robustness may decrease abruptly in case of integrity loss. Globally, they are considered moderately robust. On the other end, chlorination efficiency depends directly on chlorine doses and contact time. If any of these decrease, disinfection efficiency is strongly impacted, which makes the process weakly robust.

Each safety margin is calculated as the difference between the water quality standard and the expected quality of treated water. The latter is established based on monitoring data of existing plants, pilot studies results and literature review. The inactivation of pathogens by chlorination and UV radiation is estimated from the *Design Guidelines for Drinking Water Production Facilities* (Government of Québec 2002). For example, the calculations show that membranes and UV radiation provide very good safety margins for cysts removal. On the other hand, chlorination provides a very good safety margin for virus removal. Also, systems with no chlorination (NFUV & IEUV) do not generate disinfection by-products and thus allow a maximum safety margin for THMs.

The ease and speed of failure diagnosis and repair are evaluated based on the experience of the PE and the water treatment expert of the research team. It appears that the sub-systems differ strongly with respect to integrity monitoring mode and frequency, and with respect to ease of failure diagnosis. For example, the monitoring of membrane modules integrity is fairly complicated whereas chlorination and UV radiation can be continuously and reliably monitored. Also, the risks of membrane module obsolescence and dependency on the manufacturer are considered high, because the NF tubular membranes are manufactured by only one company. However, since there are many ion exchange resins suppliers, those risks are considered smaller for the ion exchange unit.

The investment and operation costs were provided by the PE according to quotes and real costs of similar treatment facilities. The financial computations were carried out over a 35-year period at an interest rate of 2% (standard values for the organization). The operation costs include NF membranes, UV lamps and IE resins replacement costs. For criteria 2.1 and 2.2, costs were estimated and then normalized on a 1–5 scale. As for the cost of potential system upgrading, several scenarios of stricter drinking water quality standards were elaborated according to the future standards that were in preparation in Canada at that time (Health Canada 2006), the more stringent standards in the United States and a literature review. These scenarios are about tightening the THM and turbidity standards, implementing a standard for haloacetic acids (HAAs) and tightening the requirements for pathogens removal (viruses, *Giardia* and *Cryptosporidium*). The best treatment system alternative from this point of view is the one that would be least impacted by those changes i.e. the one for which the upgrade cost to meet reinforced hypothetical standards for drinking water would be the lowest. For example, adding a membrane integrity monitoring to the NFUV would significantly increase its disinfection performance but also its operation costs. However, adding a UV reactor to the NFCL system would increase very significantly its disinfection performance without major investment or operation cost increases.

The impacts on operators (criterion 3.1) were evaluated from available technical data and the experience of the PE. Chemicals that would be used were identified for each alternative. The chemical risks were globally estimated from the probability of occurrence (frequency of use) and consequence (potential harm) of using such chemicals. Mechanical and noise risks were estimated from the equipment characteristics (pressured devices, number of pumps, etc.). The risk of heavy load was estimated from the analysis of the maintenance operations.

The technology perception (criterion 4.1) was evaluated through an internal survey which included a description of each treatment system alternative. The water quality perception by consumers (criterion 4.2) was evaluated based on the expected quality of treated water, namely its colour, the removal of taste and odour precursors (NOM) and the dosing of chlorine, which may lead to chlorinated taste and odour. The expected performances of the treatment systems were established based on monitoring data of existing plants, pilot studies results and a literature review.

The multicriteria aggregation procedure

The multicriteria aggregation procedure ELECTRE II (Maystre *et al.* 1994) was used to rank the three treatment system alternatives based on their performances on the nine criteria. The idea behind ELECTRE II is to conduct pairwise comparisons of the alternatives on each criterion in order to build binary outranking relations between pairs of alternatives based globally on all the criteria. ELECTRE II is one of the earliest multicriteria ranking methods developed based on the outranking relation principle. Although more recent procedures such as ELECTRE III are available for ranking alternatives, ELECTRE II was chosen because it is simpler to use and requires fewer parameters and thresholds than ELECTRE III.

The outranking of an alternative B by an alternative A is determined by concordance and non-discordance tests. Threshold values establish the existence or absence of an outranking relation (strong or weak) between two alternatives. From a numerical point of view, one needs to compute concordance indices and discordance indices for each pair of alternatives. The concordance index of a pair of alternatives (A, B) denoted by $c(A, B)$ validates the assertion that «A outranks B» and measures the credibility of this assertion. It is the sum of the weights of the criteria on which A is evaluated at least as good as B. The discordance index for alternatives A and B on criterion j denotes the degree to which criterion j goes against the assertion that «A outranks B». In ELECTRE II, three concordance threshold values ranging from 50 to 100% are used ($c_1 > c_2 > c_3$), as well as two discordance thresholds per criterion, d_{1j} and d_{2j}. These concordance and discordance thresholds are used to test the existence or absence of a strong or weak outranking relation between two alternatives. A lower concordance threshold value is less discriminating between alternatives than a higher one. The thresholds c_1 and c_2 are used for establishing strong outranking relations, whereas the c_3 is decisive for weak outranking relations. When the discordance index on criterion j is higher than a discordance threshold, meaning that B is better than A on criterion j by more than the threshold, we conclude that the data does not support the assertion «A outranks B». A higher discordance threshold is less discriminating between alternatives than a lower one because it allows for B to perform much better than A on the given criterion without necessarily leading to the rejection of the assertion «A outranks B». Finally, a ranking of the alternatives is obtained from the strong and weak outranking relations (Maystre *et al.* 1994).

RESULTS AND DISCUSSION

The evaluations of the alternatives according to the nine criteria are shown in Table 2. The evaluations according to criteria 1.1, 1.2, 1.3 and 3.1 are aggregated evaluations based on sub-criteria defined previously. We used the following concordance thresholds: $c_1 = 80\%$; $c_2 = 65\%$ and $c_3 = 55\%$. A value of c_2 equal to 65% means that an alternative A strongly outranks an alternative B only if the evaluations of A are better than those of B with respect to 65% of the total criteria weights. The significance of c_3 is similar for a weak outranking relation. Relatively low discordance thresholds were chosen for this study (nominal values: $d_1 = 0.5$ and $d_2 = 1$ for all the criteria). The reason being that we wanted to minimize the compensation effect and penalize unbalanced alternatives, i.e. alternatives with a mix of very good and very bad evaluations. The alternatives rankings that were established using ELECTRE II, the evaluations of Table 2 and the concordance and

Table 2 | Alternatives evaluations on a scale from 1 (worst performance) to 5 (best performance)

	Alternatives		
Criterion	**NFUV**	**NFCI**	**IEUV**
1.1 Reliability and ease of operation	3.7	2.7	3.6
Aggregate of reliability indicators	3.7	3.7	3.8
Aggregate of ease of operation indicators	3.8	2.0	3.5
1.2 Robustness and safety margin	2.8	2.9	3.1
Aggregate of robustness indicators	2.9	2.3	3.4
Aggregate of safety margin indicators	2.7	3.8	2.6
1.3 Ease of failure diagnosis and repair	3.7	2.6	3.9
Aggregate of ease of failure diagnosis indicators	4.4	2.2	3.7
Aggregate of ease of repair indicators	2.5	3.1	4.3
2.1 Total investment	3.0	2.8	3.8
2.2 Operations costs	5.0	1.5	1.4
2.3 Potential upgrading costs	3.0	3.0	2.5
3.1 Operator health and safety	3.9	3.7	3.7
3.1.1 Chemical risks	3.0	2.5	4.0
3.1.2 Mechanical risks	3.5	3.5	4.0
3.1.3 Noise	5.0	5.0	5.0
3.1.4 Heavy loads	5.0	5.0	2.5
4.1 Technology perception	4.2	3.0	2.0
4.2 Water quality perception	4.9	4.2	3.5

discordance thresholds are presented in Table 3 for the different sets of criteria weights. A full arrow from A to B indicates that A strongly outranks B, a dotted arrow indicates a weak outranking relation, whereas the absence of an arrow between A and B indicates that the alternatives A and B are incomparable.

It appears from Table 3 (second column) that NFUV is never outranked by the two other alternatives. For the weights sets 1 (technicians and engineers) and 3 (administrators) and for the average weights set, NFUV outranks strongly or weakly the two other alternatives. The preference relation resulting from weights set 2 (maintenance chief) differs from the other two by the fact that IEUV weakly outranks NFCL. From Table 3 (third column), it also appears that the rankings based on average weights and on sets 1 (technicians and engineers) and 3 (administrators) are identical: NFUV is ranked first and NFCL and IEUV are both ranked second. The resulting ranking for set 2 (maintenance chief) differs from the other result. NFUV and IEUV are both ranked first and NFCL is ranked last. This set of criteria weights is characterized by a noticeable preference for reliability and robustness of the treatment alternatives (criterion 1), since almost two-thirds of the total weights is allocated to this criterion. In summary, NFUV is the alternative that globally satisfies the different stakeholders, based on the thresholds and evaluations shown previously. As a matter of fact, this alternative was later implemented in several hydroelectric plants.

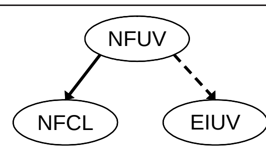
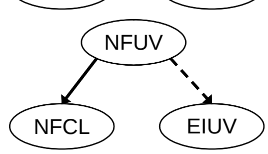
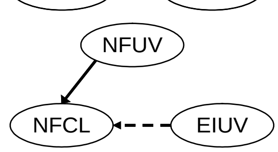
Sensitivity analysis

Since the method's parameters and the alternatives evaluations directly impact the results, it is important to conduct a sensitivity analysis to understand how the results vary with possible variations in input. The set of average weights is used for this sensitivity analysis. The results that are obtained with the other sets of weights lead to similar conclusions (Bouchard & Beauchamp 2006). The impacts of concordance thresholds variations on the alternatives ranking are shown in Figure 4. Three domains can be distinguished on this figure:

1. For $50\% \leq c_3 < 70\%$ (solid ABCDEF) the ranking is: 1. NFUV, 2. NFCL, 2. IEUV;
2. For $70\% \leq c_3 < 90\%$ (solid DEFGHI) the ranking is: 1. NFUV, 3. NFCL, 2. IEUV;
3. For $90\% \leq c_3 \leq 100\%$ (solid GHIJ) the ranking is: 1. NFUV, 1. NFCL, 1. IEUV.

In the first domain, which encompasses most of the space of possible values for c_1, c_2 and c_3, the basic ranking is preserved. Concordance thresholds have to be very high to differentiate alternatives IEUV and NFCL, whereas NFUV is always ranked first. In order to discriminate between NFCL and IEUV, c_3 has to be superior or equal to 0.7. When c_3 is superior or equal to 0.9, it is not possible to express any preference for one alternative over the others. Such a concordance threshold is extremely severe and has no practical interest.

Table 3 | Outranking relationships and alternatives rankings for different weights sets

Criterion weight set	Outranking relationships	Ranking
Mean		NFUV: 1 IEUV: 2 NFCL: 2
1 (Tech. & Eng.) & 3 (Administ.)		NFUV: 1 IEUV: 2 NFCL: 2
2 (Chief Maint.)		NFUV: 1 IEUV: 2 NFCL: 1

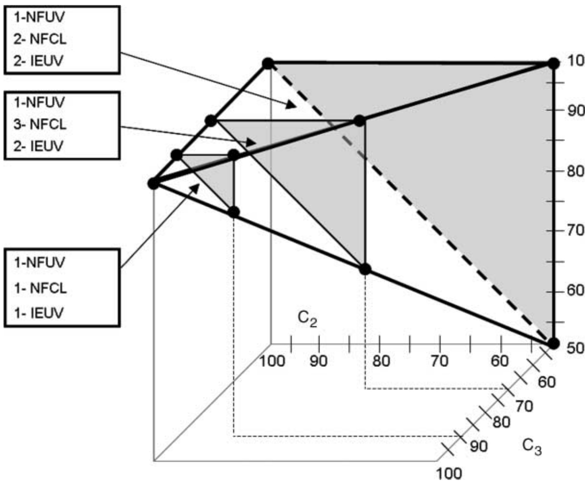


Figure 4 | Impact of concordance threshold variations on the alternatives ranking (the thick line pyramid corresponds to the domain of the possible values for c_1. c_2 and c_3).

The impacts of discordance threshold variations on the alternatives ranking are shown in Figure 5. Nominal values of $d_1 = 0.5$ and $d_2 = 1.0$ are shown by a star on the graph on Figure 5. It is important to note that all thresholds d_1, for all criteria, were varied in the same way, idem for d_2. Three domains are distinguishable on Figure 5:

1. For $d_2 \geq 0.8$: the ranking is: 1. NFUV, 2. NFCL, 2. IEUV;
2. For $0.8 > d_2 \geq 0.05$: the ranking is: 1. NFUV, 3. NFCL, 2. IEUV;
3. For $0.05 > d_2$: the ranking is 1. NFUV, 1. NFCL, 1. IEUV (not shown on Figure 5).

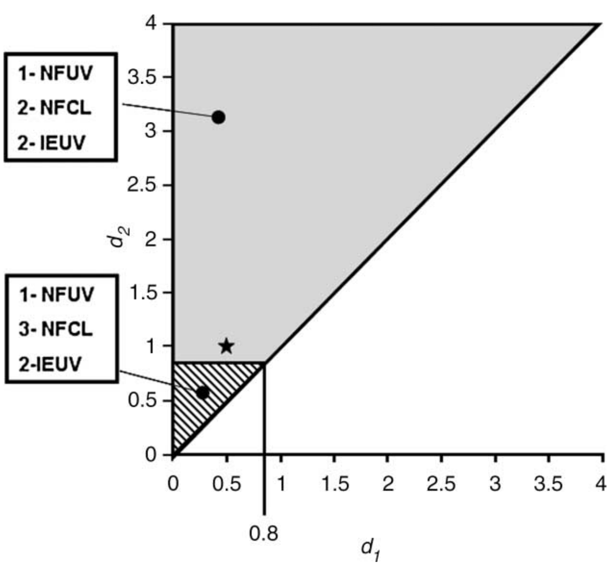


Figure 5 | Impact of discordance thresholds on the alternatives ranking.

Globally, it appears that NFUV is again always ranked first. As for the concordance thresholds, varying the discordance thresholds only affects the relative ranking of alternatives NFCL and IEUV. A more permissive discordance threshold d_2 would not change the ranking obtained with the nominal threshold values. Making this threshold more stringent ($d_2 < 0.8$) allows a distinction between IEUV and NFCL, sending NFCL to third rank. Varying the discordance thresholds has a more noticeable effect than varying concordance thresholds, because the default value for d_2, which is 1, is close to the critical value (0.8) under which the ranking changes.

Sensitivity analysis of alternative evaluations was also conducted (results not shown) by varying the evaluations one at a time by $\pm 20\%$. This was done only for criteria 1.1, 1.2, 1.3, 2.1, 2.2 and 4.2, which have the higher weights. The rankings that correspond to these modified evaluations were determined and compared with the basic evaluation. In all cases, the NFUV alternative remains first, for all the evaluations variations. This predominance comes from the fact that this alternative gets high evaluations according to several criteria and does not get any weak evaluation (see Table 2). In most cases, the ranking of NFCL and IEUV also remains the same. When the relative ranking of these two alternatives does change, IEUV outranks NFCL. Globally, evaluations for criteria 1.1, 1.3, 2.1 and 2.2 are the ones that have the biggest impact on the relative ranking of NFCL and IEUV.

CONCLUSIONS

The problem that is addressed in this paper is the selection of a small drinking water treatment system for a hydro-electrical plant. The multicriteria decision analysis process that was followed is described in detail. This process takes into account different dimensions including public health, cost consideration, system impacts on workers and perception issues. It also favours a participatory approach that includes many stakeholders. The methodology includes the construction of the water treatment alternatives set and evaluation criteria. The validation of the criteria by internal and external stakeholders and by experts confirmed the pertinence and the legitimacy of these criteria. The multi-criteria method ELECTRE II, which is based on pairwise comparisons of the alternatives, is used to aggregate the evaluations of the water treatment alternatives. The process resulted in the ranking of the three considered alternatives. Based on our analysis, it appears that the system which combines NF and UV disinfection is ranked as the best system, according to all the weightings sets of the different stakeholders. The sensitivity analysis revealed that this conclusion remains even when the parameters of the aggregation methods or the evaluations are varied, thereby confirming the robustness of the top alternative. Moreover, the weighing of the criteria by the different internal stakeholders leads to a more robust recommendation, since the same option got the first rank for all the weight sets.

Multicriteria decision aid methods like ELECTRE II are richer than simplistic methods as the weighted average calculation. However, they are more complex to implement because of the different parameters that must be set. They also require a significant involvement of the decision-makers in the selection process. On the other hand, they generate a lot of useful information and make the technological choice much more transparent. It is worth noting that the top alternative of this study has since been implemented in several hydro-electrical plants and that the internal stakeholders of the company particularly liked the multicriteria approach that allowed us to consider criteria other than the classical economic criteria. Furthermore, the approach may be easily applied to similar industrial or municipal cases. Finally, it would be interesting, in future work, to use environmental LCA to assess the global impacts of a water treatment plant and include it in a global decision aid framework.

ACKNOWLEDGEMENTS

This research was supported by funding from Hydro-Québec.

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First received 18 July 2009; accepted in revised form 23 November 2009