Selecting Sustainable Point-of-Use and Point-of-Entry Drinking Water Treatment: A Decision Support System

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

A copy of the developed decision support system can be acquired by contacting the author.

Mention of trade names or commercial products does not constitute endorsement or recommendation for their use by the author or funding agencies.

Abstract

Point-of-use (POU) and point-of-entry (POE) water treatment are forms of decentralized water treatment that are becoming increasingly sought alternatives for ensuring the safety of drinking water. Although the acceptance of POU and POE systems is still the subject of some debate, it is generally acknowledged that they have a role to play in drinking water treatment. However, some of the main drivers for the increase in the use of POU and POE alternatives include: (1) the emergence of new technologies with high removal efficiencies of target contaminants; (2) the enhanced certification system of POU and POE treatment devices and components which ensures that devices have been well engineered to achieve defined contaminant removal targets and do not add contaminants from materials of construction; (3) the inclusion of POU and POE systems as acceptable means to comply with drinking water standards; and (4) the concerns voiced by consumers in several surveys regarding the safety of centrally treated drinking water; which, regardless of whether or not these concerns are justified, have led to an increase in the use of POU and POE treatment systems. With the commercialization of these devices the task of selecting a suitable device for treatment has become cumbersome. When the inherent complexity of a particular drinking water treatment task is added to the mix, a complex decision making situation is created. Thus the need for designing a decision support tool to compare and select POU and POE treatment systems was evident. Currently the best decision aid for selecting POU and POE systems is NSF International's listing of the devices and their contaminant reduction claims.

A significant contribution of this research is the depiction of an appropriate conceptual framework for developing usable and valid decision support systems (DSSs) to select or design water or wastewater treatment systems. A thorough investigation of the methods used to develop DSSs benchmarked a systematic approach to developing DSSs, which includes the analysis of the treatment problem(s), knowledge acquisition and representation, and the identification and evaluation of criteria controlling the selection of optimal treatment systems. Finally, it was concluded that there is a need to develop integrated DSSs that are generic, user-friendly and employ a systems analysis approach.

Another significant contribution of this research is applying a systems analysis approach to outline aspects of implementation, management, and governance of POU and POE water treatment systems. The analysis also included a timeline of the progress of POU and POE treatment from regulatory, industry and certification, and research perspectives. Results of the analysis were considered the first

step of a conceptual framework for the sustainability assessment of POU and POE treatment systems which acts as the basis for developing a decision support system that will help select sustainable POU or POE treatment systems. In the context of POU and POE treatment, sustainability encompasses providing: (a) safe drinking water to help maintain good human health and hygiene; (b) minimum negative impact on the environment; (c) better use of human, natural, and financial resources; (d) a high degree of functional robustness and flexibility; and (e) cultural acceptance thus encouraging responsible behavior by the users.

The most significant contribution of this research is developing, for the first time, a set of sustainability criteria, objectives, and quantifiable indicators to properly assess the sustainability of the various POU and POE alternatives. Twenty five quantitative and qualitative indicators covering technical, economic, environmental, and socio-cultural aspects of implementing a POU or a POE system were defined. Results of a survey of experts' judgment on the effectiveness of the developed list of indicators generated 52 comments from 11 experts, which helped in refining and enhancing the list.

The conceptual framework for assessing the sustainability of POU and POE systems represented a blueprint for building the decision support system. Decision logic and cognitive thinking was used to formulate the calculation of the 20 refined indicators. The Analytical Hierarchy Process (AHP), a recognized Multi-criteria Decision Analysis (MCDA) tool, was employed to construct the structural hierarchy of sustainability indicators. Pairwise comparison was used to help in the analysis of indicators' relative importance and develop the indicators' weights. A survey was designed to develop the relative weights of the indicators based on the average response of 19 stakeholders to a series of pairwise comparison questions pertaining to the relative importance of the indicators.

Finally, the practical contribution of this research is the development of, for the first time, a new Decision Support System for Selecting Sustainable POU and POE Treatment Systems (D4SPOUTS) suitable for a particular water treatment case. The MCDA technique explained above is combined with designed screening rules, constraints, and case characteristics to be applied to a knowledgebase of POU and POE treatment systems incorporated in the DSS. The components of the DSS were built using Microsoft® Excel® and Visual Basic® for Applications. The quality of the DSS and aspects of its usability, applicability, and sensitivity analysis are demonstrated through a hypothetical case study for lead removal from drinking water. This research is expected to assist water purveyors, consultants, and other stakeholders in selecting sustainable and cost effective POU and POE treatment systems.

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Dedication

I dedicate this work to my wife, the new and lasting (Allah willing) blessing in my life.

Table of Contents

List of Figures

List of Tables

List of Acronyms

AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
ANSI	American National Standards Institute
BCMOH	British Columbia Ministry of Health
CBR	Case Based Reasoning
CSA	Canadian Standards Association
CWA	Clean Water Act
D4SPOUTS	Decision Support System for Selecting Sustainable Point-of-Use and point-of-entry drinking water Treatment Systems
DBP	Disinfection Byproducts
DSS(s)	Decision Support System(s)
DWPA	Drinking Water Protection Act
DWT	Drinking Water Treatment
DWTU	Drinking Water Treatment Unit
ELECTRE	ELimination and Choice Expressing the REality
ES	Expert Systems
GPA	Global Program for Action
GRA	Grey Relational Analysis
IWRM	Integrated Water Resources Management
IWWT	Industrial Wastewater Treatment
KBS	Knowledgebase Systems
LCC	Life Cycle Cost
MAUT	Multi-Attribute Utility Theory
MCDA	Multi-Criteria Decision Analysis
MINLP	Mixed Integer Non-Linear Programming
MLA	Multi-Level Amalgamation
NSF	NSF International
OMOE	Ontario Ministry of Environment
POE	Point-of-Entry
POU	Point-of-Use

PROMETHEE	Preference Ranking Organization METHod for Enrichment Evaluation
QL	Qualitative
QN	Quantitative
SDWA	Safe Drinking Water Act
SMART	Simple Multi-attribute Rating Technique
UNEP	United Nations Environmental Program
USEPA	United States Environmental Protection Agency
WQA	Water Quality Association
WWT	Wastewater Treatment

Chapter 1
Introduction

When it comes to drinking water, the challenge faced by many jurisdictions is to provide safe drinking water to consumers while ensuring minimum environmental, economic, and socially adverse effects. There are a wide variety of strategies and technologies that could fulfill this goal. The traditional practice involves large centralized drinking water treatment plants and long distribution networks to reach consumers. Two main concerns have been associated with this practice: 1) the multiplicity of emerging contaminants resulting in setting new water regulations, and the consequent elevated costs of upgrading central plants to cope with stricter drinking water regulations; and 2) the difficulty associated with controlling contaminants introduced in the distribution system including disinfection byproduct formation and lead dissolution.

Decentralized treatment has been proposed to complement or replace centralized treatment to overcome some challenges that the latter may face. Moreover, Silverman (2007) discussed the benefits of surpassing regulatory standards in drinking water provision by using decentralized treatment as a polishing step following centralized treatment. The smallest scale at which drinking water treatment can be implemented is at the point-of-use (POU) level. POU devices usually only treat water intended for direct consumption (drinking and cooking), and are typically installed at a single outlet or limited number of water outlets in a building. A slightly larger scale is the point-of-entry (POE) treatment level, where devices are typically installed at the inlet to treat all water entering a single home, business, school, or facility (USEPA, 2006a, 2006b; AquaVic, 2007).

Although substantial advances in centralized water treatment have helped in enhancing the sustainability and robustness of this task, decentralized and small water systems still linger in achieving an equivalent level (Anderson and Sakaji, 2007). The reasons are numerous, and perhaps the least of which are financial constraints faced by small systems. For decades the compliance of small water systems to increasingly stricter regulations seemed to be an insurmountable task, especially in remote and rural areas where the necessary expertise and financial resources are often unavailable. This has led to numerous incidences of outbreaks caused by waterborne pathogens and other adverse health effects resulting from water contaminants in small communities (Dupont, 2005; AquaVic, 2007).

1.1 Problem Statement

The growing interest in POU/POE devices has led to an overwhelming increase in the number of commercial devices that are marketed as potential solutions to drinking water problems. This leaves consumers and community water suppliers with the difficult task of choosing from among these devices. According to the most recent study, only around 34% of the devices available on the market were certified in the early 2000's, which makes the decision even more challenging (Lavoie, 2000).

Furthermore, in many cases, there is limited experience with the use of POU/POE devices which complicates the proper selection of a treatment device. The current experience does not match the expected increase in the adoption of POU/POE devices (AquaVic, 2007). Moreover, the acceptance of POU/POE technologies as compliance alternatives to drinking water regulations in Canada is expected to increase their use in many situations. This calls for an approach where the available experience can be accessible to interested groups from consumers and water purveyors including those who do not necessarily have an extensive background in water treatment.

In the course of investigating the efficiency of POU/POE devices some studies focused on removal of specific metal contaminants and disinfection byproducts (DBPs) (Sublet *et al.*, 2003; Ahmedna *et al.*, 2004b; Levesque *et al.*, 2006; Xia *et al.*, 2007). Furthermore, numerous POU/POE treatment technologies have been investigated to assess their removal of the more important contaminants such as arsenic; some of the more successful technologies include activated alumina, activated carbon, ion exchange, distillation, reverse osmosis, and nanofiltration (Souter *et al.*, 2003; Thomson *et al.*, 2003; Koning and Thiesen, 2005; Slotnick *et al.*, 2006; Mohan and Pittman, 2007; Xia *et al.*, 2007).

Reports and guidelines developed to aid in the selection of appropriate POU/POE technologies have focused on technical factors to ensure the effectiveness of a treatment system (USEPA, 2006a, 2006b; AquaVic, 2007). These factors include: (i) site-specific water quality issues, (ii) annual maintenance costs, (iii) operator skill required, and (iv) regulations and guidelines. However, a more holistic approach is to consider the sustainability of the treatment system. A water sector that follows a participatory, democratic, holistic and integrated decision making approach to water management can be described as sustainable (Starkl and Brunner, 2004). Objectives of sustainability vary depending on the context, for a water system to be sustainable it has to strive to achieve: (a) minimum environmental stress; (b) safe water for health and hygiene; (c) better use of human, natural, and financial resources; (d) a high degree of functional robustness and flexibility; and (e) cultural acceptance to encourage responsible behavior by the users (Hellstrom *et al.*, 2000).

1.2 Motivation and Objectives

The process of implementing a POU/POE water treatment system at a community level is usually divided into two phases. Phase one includes the screening of alternatives on the market and selection of candidate systems. The second phase involves pilot testing of alternative systems and selecting the one with adequate performance and reasonable cost. The first phase is dependent on experience that is often not available. Hence, regulators, city engineers, and water purveyors can benefit from a decision support system for screening and shortlisting candidate devices that can be implemented. An integrated study was thus needed to develop a decision aid to select candidate POU/POE treatment devices.

Depending on the technology used in a POU/POE device, the expected performance and removal efficiency of the device can be estimated. The process of certification can help in preparing a database of the available POU/POE devices and their treatment claims, although further investigation is needed to develop a comprehensive knowledgebase of the sustainability assessment of each treatment device. A sustainability-based selection process for POU/POE treatment devices needs to be designed, validated and implemented. The goal of this research was to develop a decision support system that focuses on aiding in the selection of a sustainable point-of-use or point-of-entry treatment devices.

The specific objectives of this research were to:

1. Construct a knowledgebase of the available POU/POE devices and their various characteristics;
2. Provide a standardized method for assessing the sustainability of POU/POE treatment alternatives; and outline a list of indicators and criteria that contribute to the sustainability rating.
3. Provide an evaluation method that enables rating and comparing POU/POE treatment alternatives through a decision algorithm.
4. Integrate the components of a decision support system to allow interested stakeholders with various backgrounds from water purveyors, regulatory agencies etc. to compare treatment alternatives and evaluate results through a consistent, simple and elaborative method.
5. Validate and verify the developed decision support system through a hypothetical case study and a sensitivity analysis.

1.3 Thesis Structure

The thesis is composed of four main chapters that were written in journal article format. Two of these chapters have already been published and the other two are still in the publishing process at the time of writing. The logical and sequential flow of ideas throughout the four articles helped structure the thesis in this form. Figure 1.1 below describes the structure of the thesis and the relevance of each chapter.

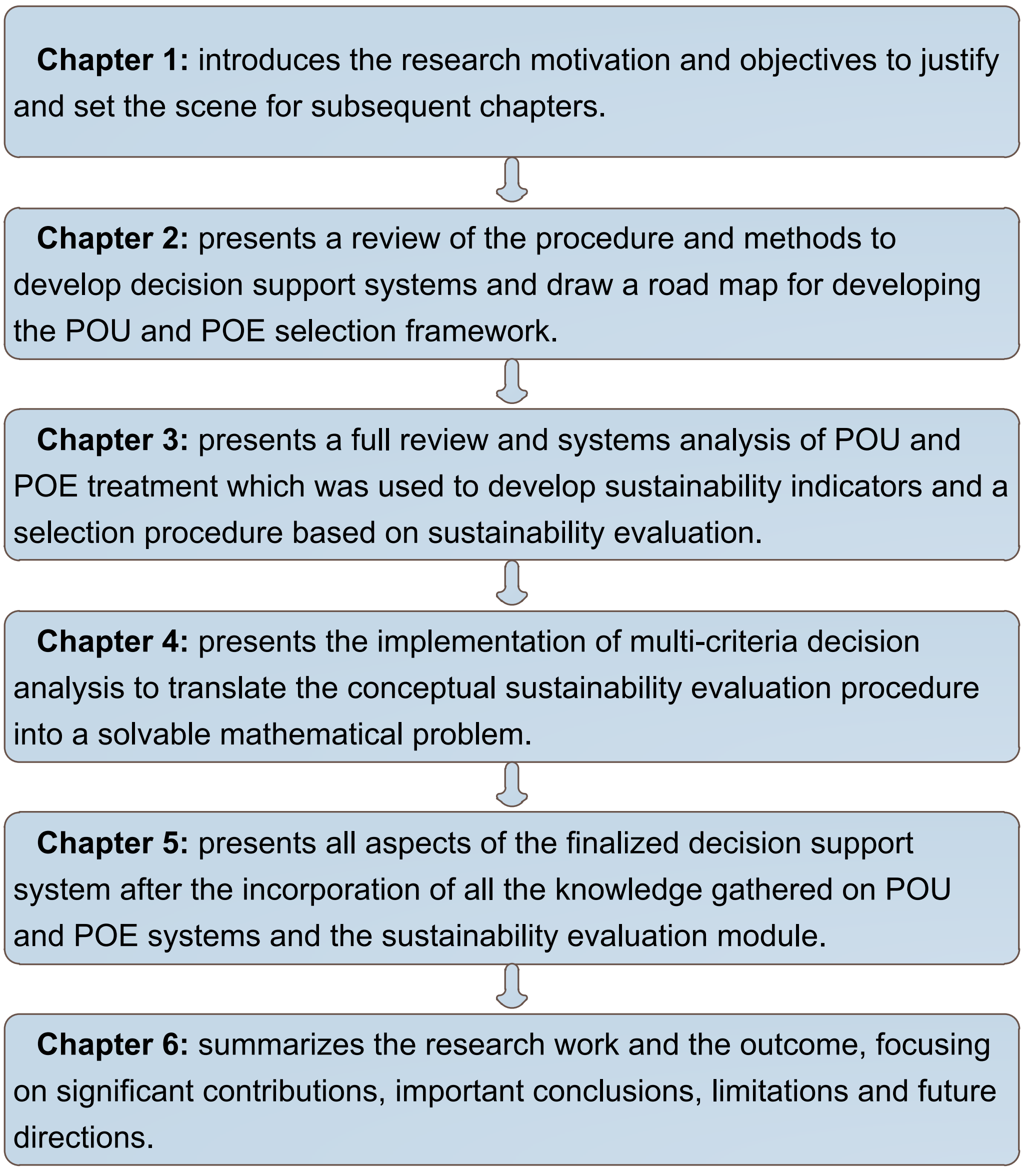

Figure 1.1 Thesis structure

Chapter 2
Decision Support Systems in Water and Wastewater Treatment Process Selection and Design: A Review

This chapter is based on a published article with the same title in Journal of Water Science and Technology (July, 2009) volume 60 issue 7 pages 1757-1770. Cited references are in the consolidated list of references at the end of thesis.

The article focuses on the procedure to develop a decision support system. A review of the various methods and techniques used in developing water related decision support systems was done. An important result was the depiction of the stages to develop a decision support system. The article is intended to set the scene for designing a framework to develop a decision support system to select among point-of-use and point-of-entry treatment systems.

Summary

The continuously changing drivers of the water treatment industry, embodied by rigorous environmental and health regulations and the challenge of emerging contaminants, necessitates the development of decision support systems for the selection of appropriate treatment trains. This article explores a systematic approach to developing decision support systems, which includes the analysis of the treatment problem(s), knowledge acquisition and representation, and the identification and evaluation of criteria controlling the selection of optimal treatment systems. The objective of this article is to review approaches and methods used in decision support systems developed to aid in the selection, sequencing of unit processes and design of drinking water, domestic wastewater, and industrial wastewater treatment systems. Not surprisingly, technical considerations were found to dominate the logic of the developed systems. Most of the existing decision-support tools employ heuristic knowledge. It has been determined that there is a need to develop integrated decision support systems that are generic, usable and consider a systems analysis approach.

Keywords: decision support; design support; optimization; wastewater treatment; water treatment

2.1 Introduction

Water and wastewater treatment systems are complex and dynamic in nature. The challenge of treating water to a required quality level is influenced by the various interactions of factors impacting the effectiveness of a water treatment system. The design of a water treatment train will depend on water quality, regulatory requirements, consumer/environmental concerns, construction challenges, operational constraints, available treatment technologies, and economic feasibility (MWH, 2005). Although the purpose of the treatment system being developed may be either for drinking, domestic wastewater, or industrial wastewater treatment, the problem of designing an appropriate treatment system is similar. Basically a treatment train is composed of a series of processes and the number of such processes has been steadily growing making the selection of an optimum sequence an important challenge faced by a designer (Joksimovic *et al.*, 2006).

Information technology has played an increasing role in the planning, design, and operation of water treatment systems. A decision support system (DSS) is an information system that supports a user in choosing a consistent, near optimum solution for a particular problem in a reduced time frame (Hipel *et al.*, 2008; Poch *et al.*, 2004; Sage, 1991). Efforts to develop DSSs to solve water and wastewater treatment problems in the past 20 years provide a wealth of knowledge with respect to designing and building DSSs. The range of applications of DSSs in water treatment problems is overwhelming; issues include selection and design of treatment processes, sequencing of selected processes either in parallel or in series in a treatment train, and monitoring and control of treatment plants (Evenson and Baetz, 1994; Hidalgo *et al.*, 2007). Benchmarking advances in DSSs development is necessary to provide a knowledge roster to benefit engineers and researchers who are either not familiar with DSSs or who may be familiar but need more knowledge to consider in future development and application of water treatment DSSs. This chapter explores the various decision support approaches and methods used in the analysis, interpretation, and solution of water treatment process selection, and sequencing and design of these processes. Having a compendium of these approaches and methods can help developers of DSSs select the approach most suitable to the problem under consideration.

2.2 Developing a Water Treatment Decision Support System

Several procedures have been proposed to select and sequence treatment processes, and design water and wastewater treatment facilities. The stages for developing a water treatment DSS are similar regardless of the application; a depiction of the four stages for developing a DSS for a water treatment problem is shown in Figure 2.1. The first stage includes the analysis and interpretation of the problem at hand. This stage can either be problem specific, where the concern can be with a specific contaminant or treatment process; or the analysis can be generic, where different processes are considered to remove various contaminants. The second stage includes developing the reasoning models where the knowledge gathered from the first stage can be represented numerically, or in heuristic "rule of thumb" form. The third stage represents the actual decision support where alternatives are generated, evaluated, and process selection and design occurs. In this stage optimization methods play an important role in incorporating all factors to arrive at a best possible alternative. The final stage ensures usability by validating and verifying the DSS logic, as well as enhancing user interactivity with the developed DSS.

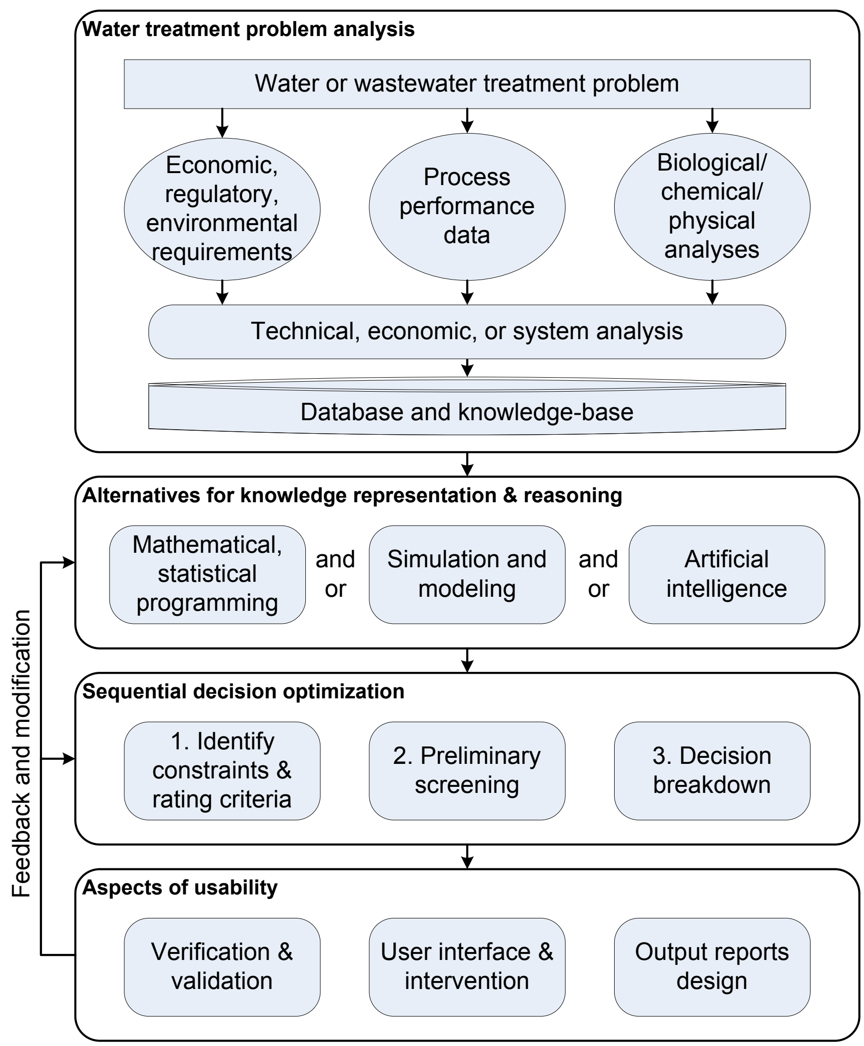

Figure 2.1 Stages of developing a water treatment decision support system

This four-stage approach is not always structured as shown below and the development procedures of various DSSs usually remain very distinct and project-specific (Gachet and Sprague, 2005).Especially, many developed DSSs fail to consider aspects of usability in the design of the DSS. In many cases the distinction between the stages of developing a DSS is not delineated. Some of the DSSs reviewed in this study are described in Table 2.1; the selected DSSs in this table are the more developed and automated rather than the conceptual ones. The various methods and techniques used to develop the DSSs and the features increasing their usability are mentioned in the table. The following sections discuss these methods and techniques in detail.

2.3 Water Treatment Problem analysis

There are more than 20 factors that should be considered when selecting a water treatment process and designing a treatment train (Metcalf & Eddy, 2003; MWH, 2005). However, most developed DSSs only consider the major technical and economic factors of selecting a water treatment process such as contaminant removal efficiency and capital cost. The reason is that many of the non-technical factors influencing the selection of a water treatment process are unquantifiable, thus there is less data available for them, and the extent of their influence is variable. This stage, as shown in Figure 2.1, is primarily concerned with extracting information about the treatment problem from available data sources. The term data refers to the numbers and figures recorded in reports and databases; whereas the term information refers to the transformation of data into meaningful terms that help define the problem at hand (Bellinger *et al.*, 2004). In general, there are three approaches to choose from when analyzing treatment alternatives (technical design, technical and economic analysis, and systems analysis).

2.3.1 Technical Design

Selecting a water treatment process is inherently a technical design task. Nevertheless, as is clear from Table 2.1, this approach is somewhat outdated as decision makers realized the importance of considering non-technical factors in their decisions. It is currently only used when the technical problem is of considerable difficulty to justify the time and money invested in the developed technical DSS. As shown in Figure 2.2, the scope of this approach focuses on the technical aspects of the system and the objectives constitute a list of performance targets for the effective removal of certain contaminants that are achieved through a detailed design approach (Evenson and Baetz, 1994; Hudson *et al.*, 1997; Bagajewicz, 2000; Sairan *et al.*, 2004). Although this might sound like a strictly

Table 2.1 Summary of some reviewed water treatment decision support systems

Model name	Scope	Approach	Employed techniques	Strengths	Reference
--	WWT	Technical & economic	Rule-based, heuristic search, neural networks	• Certainty factors for the developed rules	(Krovvidy *et al.*, 1991)
--	WWT	Technical & economic	Process modeling, mathematical programming	• Solves mass balance on a treatment train • Graphical display of designs	(Kao *et al.*, 1993)
--	WWT	Technical & economic	Case-based reasoning, heuristic search	• Define cost per unit removal of contaminant	(Krovvidy and Wee, 1993)
--	IWWT	Technical design	Knowledge-based expert system	• Allows user intervention during selection	(Evenson and Baetz, 1994)
SOWAT	WWT	Technical & economic	Rule-based, heuristic search, fuzzy logic	• Fuzzy functions for technology performance • Ability to check a user defined train	(Krovvidy *et al.*, 1994)
--	WWT	Technical & economic	Expert system, fuzzy logic	• Certainty factor for technology treatability • User defined fuzzy preference of technologies	(Yang and Kao, 1996)
MEMFES	IWWT	Systems analysis	Expert system, simulation, analytical hierarchy process	• A tutor provides justification for outcome • Surveyed the system's user-friendliness	(Heller *et al.*, 1998)
--	WWT	Technical & economic	Simulation, issue-based information systems	• Reports describe the deliberation over a decision • Searching design records using keywords	(Rodriguez-Roda *et al.*, 2000)
SANEX	WWT	Systems analysis	Conjunctive elimination, multi-attribute utility technique	• Multi-disciplinary set of sustainability indicators • Multilevel amalgamation used for rating	(Loetscher and Keller, 2002)

Model name	**Scope**	**Approach**	**Employed techniques**	**Strengths**	**Reference**
--	IWWT	Technical & economic	Knowledge-based system, heuristic search	• Easy update of process database • Possible communication with other programs	(Wukovits *et al.*, 2003)
WAWTTAR	DWT WWT	Systems analysis	Modeling and simulation, screening, multi-criteria decision analysis	• Output: least cost alternative, assesses risk, and more • Community specific data considered in the decision	(Finney and Gerheart, 2004)
WASDA	WWT	Technical design	Rule-based, design equations	• Friendly user interface • Process design calculation module	(Sairan *et al.*, 2004)
WADO	IWWT	Technical & economic	Rule-based, mixed integer nonlinear programming	• Investigates regeneration opportunities from water used in industrial processes	(Ullmer *et al.*, 2005)
WTRNet	WWT	Technical & economic	Modeling & simulation, linear & NL programming, genetic algorithm	• Provides user guidance for treatment train selection through either an expert or a stepwise approach	(Joksimovic *et al.*, 2006)
--	WWT	Systems analysis	Analytical hierarchy process, grey relational analysis	• Allows comparison between alternatives considering the entire criteria	(Zeng *et al.*, 2007)
--	DWT	Systems analysis	Bayesian probability networks	• Considers performance uncertainty • Variables measuring impact on public health	(Zhu and McBean, 2007)

Where WWT: wastewater treatment; IWWT: industrial wastewater treatment; DWT: drinking water treatment mathematical optimization problem, often heuristics and expert knowledge are used to account for non-quantitative design aspects. Additionally pilot studies may be needed to quantify the set of variables considered in the analysis of the studied alternatives (Joksimovic *et al.*, 2006). Even within the scope of technical effectiveness the objectives often differ according to the source water and type of treatment problem at hand.

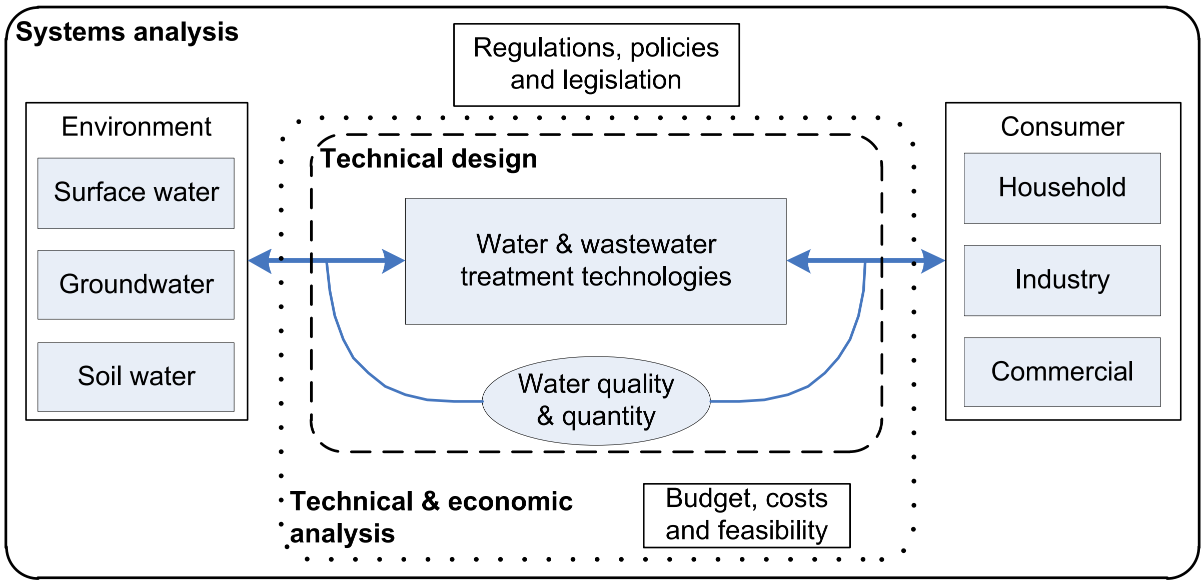

Figure 2.2 Approaches to water treatment problem analysis and their respective scopes

2.3.2 Technical and Economic Analysis

Once the technical issues are properly addressed, financial viability and cost minimization together form the second major objective in searching for an optimum solution (Krovvidy, 1998; Hidalgo *et al.*, 2007). This approach became more common during the late 1990s as shown in Table 2.1, when it was recognized that advances in technology led to corresponding economic impact forcing many DSS developers to consider cost in their design (Figure 2.2). Evaluating the costs of different alternatives can be done in numerous ways, it can be as simple as a subjective classification of the cost category of each alternative, or it can be more complex by developing cost functions that require actual local market studies (Ahmed *et al.*, 2003; Hidalgo *et al.*, 2007). Cost can also be confined to capital or investment cost or it can include operation, maintenance, and residuals disposal costs (Petrides *et al.*, 1995; Heller *et al.*, 1998; Comas *et al.*, 2003; Flores *et al.*, 2007).

In some DSSs there is an inclination towards expressing the various selection criteria in terms of money (Bick and Oron, 2005). Cost-benefit analysis or life cycle costing of a treatment system makes it easy to compare the various alternatives in terms of monetary value. However, since many social and environmental costs are difficult to quantify they thus cannot be incorporated in the analysis rendering the approach less comprehensive.

2.3.3 Systems analysis

Many perceive that designing a water treatment scheme should take into consideration not only technical aspects but also social, political, economic, legislative and even climatological features of the area intended to be served (Hidalgo *et al.*, 2007). A systems analysis approach includes choosing from a wide variety of treatment alternatives in view of an exhaustively defined working environment (Comas *et al.*, 2003). It considers the interactivity of the treatment alternative with all the affected surroundings allowing for sustainability based selection of treatment systems (Tang *et al.*, 1997; Balkema *et al.*, 2001; Comas *et al.*, 2003; Hidalgo *et al.*, 2007).

In general, it can be concluded that the above methodologies can lead to different insights about the characteristics of the various water treatment systems. In Figure 2.1 we show the difference in scope between the various approaches to a water treatment problem analysis. Technical analysis provides specific insights into performance efficiency and effectiveness. Economic analysis focuses on real costs, and systems analysis considers the bigger picture that includes the aspects of cost, technical performance, as well as social, legal, and environmental interactions (Balkema *et al.*, 2001). Generally speaking, the outcome of a DSS is more reliable when it adopts an integrated approach to problem analysis and solution; and in so doing it is also more likely to bring about a decision that is more sustainable.

2.4 Alternatives for Knowledge Representation and Reasoning

Typically, after analyzing the problem at hand a knowledge acquisition stage is initiated where relevant information is extracted from sources such as publications, expert interviews, and case studies. The term 'knowledge' is used to denote the reasoning and interpretation of information gathered from data sources (Bellinger *et al.*, 2004). Knowledge acquisition is a fundamental and typically tedious stage. Some developed DSSs incorporate an automated learning system that extracts knowledge from databases and users' input. The learning system should allow for augmentation with knowledge obtained from other sources, and it is usually an independent module in the DSS

(Krovvidy *et al.*, 1991). The acquired knowledge can be represented by one or a combination of methods including mathematical programming, artificial intelligence systems, and stochastic or deterministic process-based simulation models (Poch *et al.*, 2004) as shown in Figure 2.1 and Table 2.1. The choice among these methods is dependent on the type and complexity of the available knowledge and the set objectives.

Any attempt to develop a DSS to aid in the selection/design of water treatment trains has to include a conceptual stage where the results of the problem analysis can structure the theories and strategies governing the selection/design procedure. For example, in the case of wastewater treatment one strategy can be to break down the problem into four decision levels: pre-primary, primary, secondary, and tertiary treatment (Freitas *et al.*, 2000); or outlining the selection procedure among alternatives in the form of a decision flow chart (Flores *et al.*, 2007). These conceptual methods can guide the designer to select or design a system that will fulfill the preset objectives; however, without automation they require substantial effort to successfully follow them. Several knowledge representation methods used to allow the automation of the selection and design process in water and wastewater treatment DSSs are discussed below.

2.4.1 Mathematical Programming

Mathematical programming used to solve water treatment problems has been reviewed (Bagajewicz, 2000). This approach focuses largely on the technical aspects of the design and is mainly concerned with optimizing the solution as discussed later in this chapter. Although mathematical programming has been successfully used in designing an optimum treatment train, it is debatable whether real world design problems are presentable in a mathematical model. Integer, linear, nonlinear, and mixed programming, as well as, heuristic algorithms, are commonly used in modeling a problem and outlining an objective function. Although mathematical programming methods are used for knowledge representation, they are more often considered as optimization tools (Balkema *et al.*, 2001; Joksimovic *et al.*, 2006).

2.4.2 Simulation and Modeling

Process simulation and modeling helps to define and quantify relationships between the process performance and design variables in the form of a mathematical relationship. Simulation plays an important role in generating design alternatives and estimating their performance under various conditions (Heller *et al.*, 1998; Rodriguez-Roda *et al.*, 2000; Joksimovic *et al.*, 2006; Flores *et al.*, 2007; Hlavinek and Kubik, 2008). Mass and energy balances have been used to simulate processes, estimate effluent characteristics, and suggest process modifications to improve performance (Petrides *et al.*, 1995). The influence of process uncertainties on train performance was considered using Monte-Carlo simulation to generate alternative wastewater treatment trains (Chen and Beck, 1997; Benedetti *et al.*, 2008). Furthermore, simulation can be used to test the effectiveness of the selected treatment train (Ullmer *et al.*, 2005).

2.4.3 Artificial Intelligence Methods

Expert systems (ES) are knowledge-based systems (KBS) which emulate human reasoning using knowledge within a particular discipline (Heller *et al.*, 1998). Most water treatment problems rely on the application of certain rules of thumb. Applying heuristic rules based on experience in selecting and ordering of water treatment units has gained popularity in the past couple of decades (Krovvidy *et al.*, 1991; Yang and Kao, 1996; Hudson *et al.*, 1997; Heller *et al.*, 1998; Freitas *et al.*, 2000; Ahmed *et al.*, 2003; Comas *et al.*, 2003; Wukovits *et al.*, 2003). The challenge of ES lies in the knowledge acquisition phase where established knowledge can be obtained from domain experts and relevant publications (Sairan *et al.*, 2004). Knowledge is usually organized and documented in the form of decision trees as a precursor to developing the KBS (Krovvidy *et al.*, 1991; Yang and Kao, 1996; Freitas *et al.*, 2000; Comas *et al.*, 2003). Decision trees can then be converted to production rules by traversing each branch from the root to the leaf. Rules extracted from decision trees can be codified to discard, favor, or disadvantage alternatives based on their characteristics (Evenson and Baetz, 1994; Comas *et al.*, 2003).

Issue-based information systems (IBIS) offer a natural framework to record information as argumentation in a deliberation process and are used to map the rationale of alternative selection and design as a process of argumentation. These IBIS networks take the shape of a tree-view. The issue or question related to the design is shown at the top, the possible alternative solutions to the issue raised branch from it, and the arguments or reasons behind the selection of an alternative complete the tree-view (Tasso and de Arantes e Oliveira, 1998; Rodriguez-Roda *et al.*, 2000).

Case-based reasoning (CBR) estimates the problem solution based on the successful solutions for previous similar problems. The primary challenge for a CBR system is determining those old situations that are "similar" to the current case and organizing them in a knowledge base in a way that allows the description of the problem at hand to retrieve these relevant cases (Krovvidy and Wee, 1993). The rationale is that starting from the solution of a relevant previous case will more likely put the designer on the optimal path to a solution. Case-based systems are designed to be automatically updated with new knowledge to improve the obtained solution. Cases are viewed as a sequence of states that takes a given problem state (e.g. contaminated water) to a targeted goal state (e.g. water of acceptable quality) (Krovvidy and Wee, 1993). The main drawback of case-based systems is that they require a large number of cases to get acceptable solutions.

Neural networks (NN) mimic human brain functioning by learning how to deal with certain problems from experience, and then applying this learning to new but similar problems. Much like the human brain, its structure includes interconnected neurons that generate an output based on input signals. The number of neurons and the way they are connected influences the output. NN have been used as optimization methods, Krovvidy *et al.* (1991) used Hopfield NN to select an optimum wastewater system with minimum total cost subject to the constraint that the effluent contaminant concentrations are lower than the target limits.

Bayesian probability networks are probabilistic graphical networks that represent a set of variables and the extent to which they are conditionally independent. They are rarely used in water treatment DSSs. Bayesian probabilistic reasoning was used to define relationships among variables of raw water quality, water processing alternatives, their costs, quality of treated water, and consequences to public health (Zhu and McBean, 2007). The probability of the latter three variables given the first two variables is calculated and alternatives are screened to select the optimum.

Fuzzy logic is not a stand-alone method; rather it is a technique to manipulate incomplete, imprecise, or unreliable information and improve the representation of relationships that are not well defined in the problem under analysis. Krovvidy *et al.* (1994) use the compositional rule of inference to define a fuzzy relationship between the influent and effluent concentrations for a series of technologies in a treatment train and to define the resulting possibility values for their removal percentages. Yang and Kao (1996) use fuzzy membership functions to incorporate user defined technology preference in their DSS in a linguistic expression (low, medium, and high) which is the main advantage of using fuzzy logic.

2.5 Sequential Decision Optimization

After defining the problem at hand and representing it in any of the methods outlined previously, the final step is to select an optimum (or near optimum) solution. Despite the tendency of DSS developers to strive for reaching an optimum solution, often this step is absent in water treatment DSSs, perhaps because the very definition of an optimum solution is typically not agreed upon. In case of conflicting design objectives, the search can be for Pareto-optimal solutions where at least most objectives are satisfied without violating the others (Balkema *et al.*, 2004).

Choosing among a variety of treatment alternatives is generally based on the constraints posed by the objectives of the treatment system on the one hand and the characteristics of the treatment system on the other. Researchers and designers refer to the considerations that help in selecting a treatment alternative as criteria or factors (Figure 2.1). Although in the problem analysis stage one should come up with the criteria or objectives incorporated in the decision process, it is only in the optimization phase that a developer defines the method of quantification of the criteria as it fits to the optimization method used. These criteria are usually hard to assess or measure, thus sets of proxy indicators that best assess these criteria are used. The criteria can be generally categorized into four types: technical, economic, environmental, and sociocultural. However, most studies focus only on technical and economic indicators such as: cost of treatment, effluent quality achieved, land required, ease of operation and maintenance, resource requirement (Hlavinek and Kubik, 2008).

There are two general approaches for sequential decision optimization: (1) screening analysis by comparing different treatment systems to arrive to the optimum system; (2) decision breakdown into small parts and prioritizing the various decision criteria. Both approaches have been used individually or sequentially (Figure 2.1). The techniques used in implementing either approach vary and are discussed below.

2.5.1 Screening Analysis

If unit processes are considered separately, the number of systems increases dramatically. Compiling all the possible wastewater treatment trains, Chen and Beck (1997) have noted that as many as 50,000 alternatives need to be considered as possible trains to achieve sustainable wastewater treatment. An alternative is using screening analysis using information on local circumstances and water quality to rule out inappropriate alternatives before running the rating algorithm (Loetscher and Keller, 2002). To simplify the evaluation of multiple alternatives many DSSs employ a pre-screening stage. Objectives can be refined into numerical constraints expressed as a function of the design variables and used in the screening (Rodriguez-Roda *et al.*, 2000; Loetscher and Keller, 2002). Rules have also been used to screen alternatives incapable of contaminant removal or that cannot function in the presence of certain compounds (Wukovits *et al.*, 2003). For example, a common constraint is complying with regulatory limits on effluent contaminant concentration; this can be expressed quantitatively as contaminant X not exceeding the concentration Y.

Screening methods used vary; conjunctive elimination (CE) is one method that was used to eliminate sanitation systems that have attributes' values lower than defined cutoff levels, thus deemed technically infeasible (Loetscher and Keller, 2002). Another method is the 'generating and screening' method, which was used in screening alternative wastewater treatment trains (Chen and Beck, 1997). This method proceeds by generating as many candidate alternatives as possible and calculating a 'probability of survival' based on the relative frequencies of successfully satisfying a particular constraint and then isolating the most promising alternatives. This gives more flexibility since the focus is on generating the alternatives regardless of the selection criteria. Screening criteria are often not entirely agreed upon among designers, thus it is better to make the alternatives list independent of the criteria.

2.5.2 Decision Breakdown

As more criteria are used to evaluate an alternative, the relative importance of each criterion must be established and the overall score with respect to all the criteria must be derived. In case of conflicting criteria it is even more important to account for the differences in their impact (Heller *et al.*, 1998). In this case multi-criteria decision analysis (MCDA) can be incorporated in the DSS by breaking down the design problem.

The simplest form of MCDA is by quantifying the evaluation criteria and calculating the weighted sum score for each alternative. MCDA can become substantially more complex when there are conflicting objectives and constraints. A very wide range of MCDA methods can be used in selection problems. It can be done by trade-off methods that assign weights to different objectives such as through a pairwise comparison of alternatives using the analytical hierarchy process (AHP) or using SMART. Other non trade-off methods include ELECTRE (ELimination and Choice Expressing the REality) and PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluation) which use outranking techniques based on preference relations (e.g. alternative 'a' is better than alternative 'b' if condition 'x' applies) (Ashley *et al.*, 2008).

An example of MCDA was presented by Flores *et al.* (2007) who defined the criteria for the design of an activated sludge plant as having a set of issues, a set of design objectives, a set of evaluation criteria used to measure the degree of satisfaction of objectives by a set of alternatives, and a set of weight factors assigned and normalized to determine the relative importance of the objectives. Alternatives can be evaluated by quantifying the evaluation criteria and calculating their weighted sum score for each alternative.

Another example of MCDA is the use of the analytical hierarchy process (AHP). AHP was developed by Thomas Saaty in the 1970s (Saaty and Vargas, 2001). AHP is designed for subjective evaluation of a set of alternatives based on multiple criteria arranged in a hierarchical structure. An AHP hierarchy consists of an overall *goal*, a number of *alternatives* for fulfilling the goal, and a group of *criteria* and *sub-criteria* that relate the alternatives to the goal as shown in Figure 2.3. Ranking a large number of systems can be done by comparing the alternative systems pairwise on all selected criteria. Linguistic criteria are represented in numerical values of 1-9 using Saaty's scale for comparative judgment to denote comparative importance ranging from equal influence (1) to extremely higher influence (9). In this way, a decision matrix is built for each indicator. These matrices are combined by normalizing and calculating the geometric mean to reach a final decision (Ellis and Tang, 1991; Tang *et al.*, 1997; Bick and Oron, 2005).

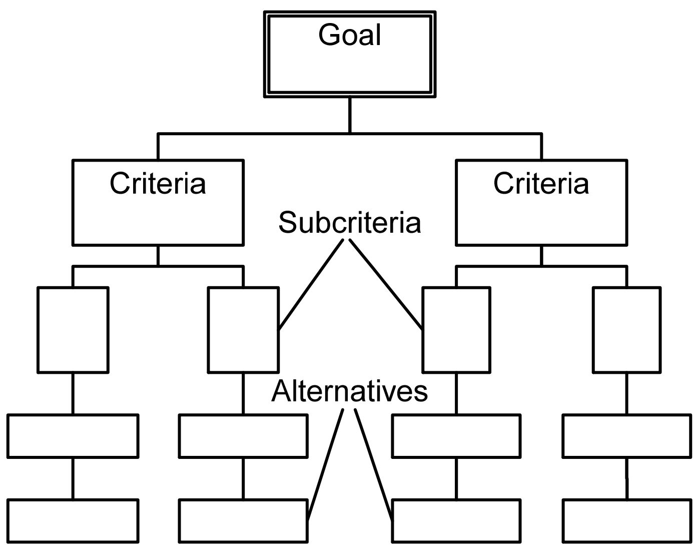

Figure 2.3 Typical hierarchical structure implemented in an AHP optimization technique

AHP ignores the complicated interrelationships among multiple performance criteria. The integration of AHP and grey relational analysis (GRA) has been used to solve the inexact problem of selecting an optimal wastewater treatment alternative to overcome the drawbacks of both methods. AHP allows using non-uniform weights on each criterion, whereas GRA enables the multi-level analysis to examine the complicated interrelationships among factors (Zeng *et al.*, 2007).

AHP has occasionally been found to be unsuitable because of the very large number of paired comparisons in a treatment selection problem. Multi-attribute utility technique (MAUT) is another technique where tree structures are used to aggregate criteria ratings on various levels in what is referred to as multilevel amalgamation (MLA) (Loetscher and Keller, 2002). The strength of MLA lies in its ability to deal with numerous criteria through tree structures; it also uses different aggregation methods at the various levels to account for the different effect each criteria has on the objective (Figure 2.4). Capital letters A, G, and M stand for different aggregation methods arithmetic mean, geometric mean, and multiplication respectively.

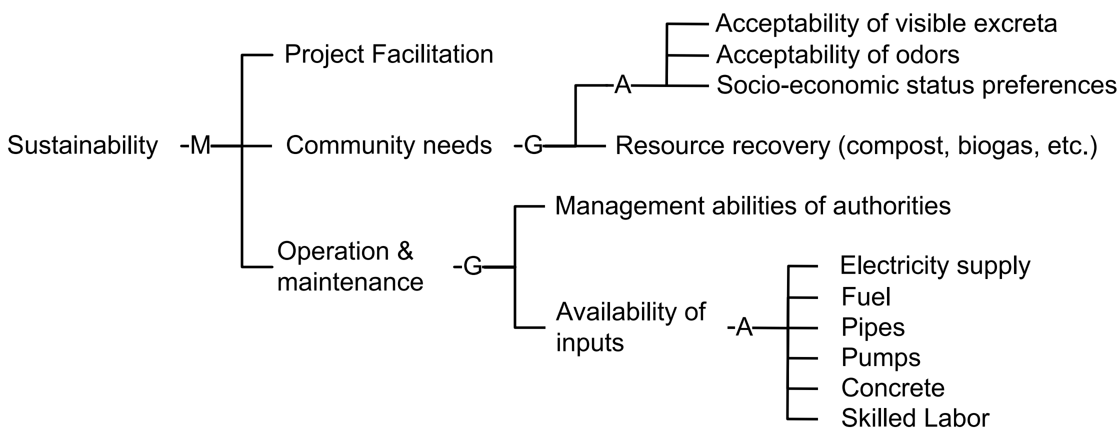

Figure 2.4 Aggregation using multilevel amalgamation

Source (Loetscher and Keller, 2002)

Simple integer programming is another common tool for multi-criteria rating of alternatives (Loetscher and Keller, 2002). More sophisticated linear and nonlinear programming methods have also been used in water treatment problems (Ullmer *et al.*, 2005; Joksimovic *et al.*, 2006). Integer and linear programming is often initially used to get good starting points for the nonlinear model variables (Balkema *et al.*, 2004; Castro *et al.*, 2007).

Whether a screening or decision breakdown approach is chosen, optimization algorithms are needed to select optimum solutions. Optimization techniques used depend mainly on the number of possible alternatives and the type of variables used in the objective function (discrete, continuous, or mixed). *Exhaustive or implicit enumeration* is used where all possible design alternatives can be explored and rated. It can only be used with alternative sets of small size which is not the case in most water and wastewater problems. *Gradient-based algorithms* built in global optimization solvers are used by researchers to search for the global optimum solution (Castro *et al.*, 2007). However, they require appropriate bounding of some of the model variables to guarantee that the objective functions are finitely valued and numerically stable. *Branch-and-bound* integer programming is a commonly used method that systematically enumerates all alternatives by growing a tree of alternatives in stages. Infeasible alternatives from one stage are eliminated by using upper and lower estimated bounds of the objective function being optimized (Evenson and Baetz, 1994; Wukovits *et al.*, 2003).

Heuristic optimization focuses on reducing computing time but it cannot guarantee a global optimum solution. Rules are employed to apply constraints on the design of a treatment train and denote changes in the quality of water after a certain treatment process. A heuristics based algorithm was used to create the optimum treatment train for a wastewater treatment problem by specifying the order of processes in a train; for example, the rule *Follow (X, Y)* is used if process X must follow Y (Krovvidy and Wee, 1993; Krovvidy *et al.*, 1994). *Evolutionary approach* optimizes, one by one, the selected variables with respect to the design objectives and process performance (Flores *et al.*, 2007). *Genetic algorithms* (GA) are artificial intelligence optimization algorithms based on the evolutionary approach. GA combines the inputs that generate the best solutions into new inputs to calculate the objective values for a new generation. Mutations are introduced during the selection process and the best 'so far' solution is reinserted. The search stops when the maximum number of generations is reached or when no improvement is made. The result is not a global optimum but rather the 'best so far' solution (Balkema *et al.*, 2004). Optimization by GA could be by screening alternative using a set of defined objectives or by decision breakdown and calculation of a maximum fitness score subject to several constraints (Hlavinek and Kubik, 2007).

Many researchers have integrated several methods to better represent the treatment problem. Krovvidy (1998) applied inductive learning, expert systems, case based reasoning, and fuzzy sets to the design problem of a wastewater treatment train. Some models, like EnviroCad use knowledge-based methods to perform process synthesis (Petrides*et al.* 1994). Ulmer *et al.* (2005) and Castro *et al.* (2007) combined heuristics and mixed integer non-linear programming (MINLP) in the design of industrial wastewater treatment systems. Sairan *et al.* (2004) used a knowledgebase method for the selection of wastewater systems and integrated it with design calculation spreadsheets to aid in the design of the treatment system. Flores *et al.* (2007) used heuristics and classification trees to cross examine the results of a multi-criteria decision-making model and provide a clear overview of the performance of the competing alternatives.

When developing a decision support method, a common approach is to start with knowledge and rule-based heuristic methods for screening and short-listing alternatives. Optimization can then be used to refine and optimize the screened alternatives (Freitas *et al.*, 2000; Loetscher and Keller, 2002). This two-phased process allows incorporation of a system approach to the analysis and selection of best alternatives, and allows the development of an integrated DSS.

2.6 Aspects of Usability

Although there have been many DSSs developed over the past years, few appear on the market as useful products. SANEX and WAWTTAR are examples of DSSs that are being circulated through the United Nations environmental programme (UNEP) Global programme of action (GPA)[1]; WAWTTAR is also circulated by the United States environmental protection agency (USEPA) as a tool to help in planning and implementing small water systems[2]. The reason other DSSs are not circulated may be that many of them are either too complicated for non-expert users or that they operate in a 'black-box' mode making it difficult for users to trust their outcome (Denzer, 2005). Aspects of usability as observed in the reviewed DSSs are explained below (Figure 2.1).

2.6.1 Verification and Validation

An important step of developing a DSS is its verification and validation. The verification of the developed DSS ranges from the basic practice of program debugging to the rigorous demonstration of the consistency, completeness and correctness of the DSS through a sensitivity analysis (Sairan *et al.*, 2004; Bick and Oron, 2005). The validity of the DSS includes making sure that the output of the system is what the user needs to solve the addressed problem.

The rigor of validation depends on the sophistication of the DSS, the objective is to examine the quality of the outcome and identify needs for further modifications. The most effective validity test is by field testing of the DSS through an application to a real world problem. However, in many cases this is not feasible. Thus, the basic approach to the validation of a DSS is through the testing of its results against expected results. Usually an expert is involved in the test and a number of cases are entered into the DSS and the deviation from the expected results is used as an indicator of validity (Heller *et al.*, 1998). Nevertheless, in design support systems it is easier to validate the results by comparing them against experimental and mathematical results.

[1]www.training.gpa.unep.org/software/
[2]www.epa.gov/OWM/mab/smcomm/tools.htm

Typical verification and validation practice was demonstrated by Sairan *et al.* (2004) by verifying a DSS through program debugging, error analysis, and data input and output analysis. Encouraging users to verify the output of a DSS against their own manual calculations is also a good practice (Sairan *et al.*, 2004). Other researchers take the validation task to a higher level, where the scope of validation is extended to assess user friendliness, output format, and relevance of results to the problem (Heller *et al.*, 1998). Furthermore, involving a range of problem stakeholders in the validation of the DSS allows for a diverse range of opinions on the DSS output (Ashley *et al.*, 2008).

2.6.2 User Interface and Intervention

The quality of user interface design and level of interactivity are the main factors influencing the usability of the DSS. In general, the user interface should encompass aspects of user input, decision analysis and reasoning, in addition to demonstrating the DSS calculations and allowing user intervention to change decision variables (Kao *et al.*, 1993; Druzdzel and Flynn, 2002). Little attention is given to the user interface when the DSS is intended as a conceptual demonstration of its utility in solving a problem (Flores *et al.*, 2007), or when it is intended for a highly specific use or for expert users who are more concerned with the theory behind the decision process (Rodriguez-Roda *et al.*, 2000; Gachet and Sprague, 2005).

DSSs that are intended for practical use allow more focus on the ability of the user to communicate with them through the user interface. If we consider a DSS that is intended to be used by a wide range of users then it is important that the user interface allow active interaction to take place. Interactivity can be in the form of adding the ability to monitor the decision process, and/or set constraints or heuristic rules that reflect the user's preferences, overriding wrong decisions, or by giving a warning message if any design standards are violated (Krovvidy *et al.*, 1991; Kao *et al.*, 1993; Freitas *et al.*, 2000). It is important that the user interface integrate the various underlying modules of the DSS; having to alternate between different modules has a deleterious effect on system usability. Often it is also important to have a help tool to guide the user through the system (Krovvidy *et al.*, 1991; Heller *et al.*, 1998).

2.6.3 Output Reports

From the review of several DSSs, it is clear that the output of a DSS used in selection and design of a water treatment system can be at any of the following levels:

1. Basic: presents the optimum solution to the problem and some parameters that help define the case under analysis (e.g. quality of influent).
2. Reasoned: presents the solution, case definition parameters, cost of various alternatives, and decision variables that influenced the results. Most DSSs fall into this level (Rodriguez-Roda *et al.*, 2000; Ahmed *et al.*, 2003; Joksimovic *et al.*, 2006).
3. Advanced: in addition to the reasoned output, advanced features may be included, such as: the next best solution, a comparison between the alternatives, cost estimates of the various alternatives, or the possibility of a "better" solution in case an input variable changes (Comas *et al.*, 2003).

2.7 Discussion

Water treatment process design and decision support has grown from a humble technical design problem in the early nineties to a complex integrated decision task where various aspects are considered. This growth in the complexity of treatment alternative evaluation has prompted the use of several approaches to assist the decision-making process. To decide whether or not a DSS needs to be developed, one has to consider several elements:

1. Level of complexity of the decision process: the more complex the decision, the more likely that a DSS is needed.
2. How promptly a solution is needed: even if the decision-making process is simple, one might need a DSS to assist with frequently addressed issues that require essentially instantaneous decisions.
3. Availability of expertise at the point of application: if assembling a roundtable of experts to solve the problem at hand is feasible then a DSS is not needed. However, this is often not the case, especially with water issues that are health related.
4. Degree of specificity of a water issue: if the problem is too specific then developing a DSS is discouraged because the investment in a DSS is not justified. However, in rare cases the decision considered is so complex and will have such a significant impact that the cost of investing in a DSS is no longer relevant (e.g. a DSS for planning of a particular watershed).

Water and wastewater DSSs have evolved from being dominated by the use of conceptual design and decision-making frameworks to the current use of various sophisticated decision-making methods. The challenge here is that of every engineering problem, i.e. striking a balance between the work invested in the DSS and the required accuracy of its outcome. Some DSSs focus on the detailed design of the water treatment system ignoring other socioeconomic and environmental aspects, while others adopt a holistic approach to the problem but fail to produce detailed designs.

Few of the reviewed DSSs are available for real world use and most are designed for local needs. The reasons for this are mainly related to the drivers for developing the DSS to begin with. Most of the DSSs that are being used in the real world were supported and funded by organizations or companies that intended that the developed system be used. Other DSSs that were developed to test or demonstrate the applicability of a particular method on the issues of water and wastewater treatment have had limited or no application in the real world.

The quest to produce a global DSS applicable to any water treatment problem in any context is not justified since there are too many variables related to local conditions to be accommodated by the current level of DSS sophistication. However, efforts to make use of the knowledge incorporated in the developed DSSs have yet to be made. The goal of the developer should be to produce a good DSS. In general, a good DSS should be: (i) based on a systems analysis approach; (ii) capable of acquiring, representing, and analyzing knowledge related to the issue at hand; (iii) flexible and capable of dealing with missing or uncertain data; (iv) adequately interactive with the user and user friendly; and (v) produce useful output and be capable of justifying it.

It is unavoidable that the DSS developer will have to choose, on a case-by-case basis, the most suitable technique applicable for the particular problem at hand. Here are a few questions to address before developing a DSS, to ensure its usability and success:

1. Should the DSS address a specific system tailored to the needs of only one application, or should it be a generalized DSS from the start, which clearly means that there is a more substantial investment (Denzer, 2005)?
2. Is the intended outcome of the DSS to provide the optimal solution to a problem or is it to get a ranked list of possible solutions?
3. Is the DSS addressing strictly a design problem or should it include other economic and social aspects which will require the involvement of all stakeholders?
4. Is the DSS intended to be an integrated system with non-technical aspects of the decision taken into consideration?

5. Is it possible to utilize knowledge bases of other previously developed DSSs? And how can the design of the new DSS allow for sharing knowledge with other DSSs?

2.8 Conclusions

The purpose of this chapter was to provide insight into what a developer encounters when constructing a decision support system (DSS) for water and wastewater treatment process selection and design. It identifies the framework necessary to develop a decision support system, to facilitate the selection of developing tools, and to provide guidance on the implementation of the developed DSS within the overall context of water treatment. One main conclusion from this review is that the scope of the DSS, its intended use, and the elements considered are the main factors influencing the way a DSS is constructed. The application of the reviewed methods in the field of water treatment decision-making varies considerably.

The systems analysis approach is yet to be given extended attention as the most comprehensive approach to problem analysis in water and wastewater treatment process selection and design. This review confirmed that technical and economic considerations are still the basic criteria in evaluating alternatives, mainly focusing on contaminant removal. However, few DSSs have been developed to address decision-making that involves all major system components. Environmental issues coupled with social considerations have only recently been included in DSSs which set the benchmark for future DSSs.

The future of DSSs in water and wastewater treatment should focus more on integrating various data within the context of a system view of water resources management. This integration will have implications on the knowledge representation and reasoning practice. With more data of various characteristics being considered in the DSS, developers have to derive methods or combinations of methods to incorporate such variety. Also, the uncertainties in data values and reliability have to be included by adopting a probabilistic knowledge representation approach to increase the validity and credibility of the DSS's output.

Joint consideration of the environmental, technical, economic, and sociocultural factors relevant to evaluating and selecting among treatment alternatives includes multiple criteria, making the process inherently multi-objective. This will in turn make the optimization task multi-objective, leading to the need for assigning preference or importance weights to decision criteria or objectives. It is important to consider methods to decrease subjectivity of these weights through stakeholders' involvement in the early stages of DSS development.

A higher level of interactivity with the users should be the goal of future DSSs. Careful attention must be given to the various aspects of usability. User friendliness and usefulness of the DSS are the keys to the success or failure of a DSS.

Chapter 3
A Framework for Selecting Among Point-of-Use and Point-of-Entry Water Treatment Systems

This chapter is based on a published article with the title “A Framework for Selecting POU and POE Systems” in Journal of American Water Works Association (December, 2010) volume 60 issue 7 pages 1757-1770. Cited references are in the consolidated list of references at the end of thesis.

The article focuses on the procedure to properly select among the various certified point-of-use and point-of-entry water treatment systems. A systems analysis was carried out as recommended in Chapter 2. The developed framework is another step towards developing a decision support system in which the framework is automated and incorporated to select sustainable POU and POE treatment systems. A sample of the questionnaire used in this article and a summary of the results can be found in Appendix A.

Summary

Although the acceptance of point-of-use (POU) and point-of entry (POE) systems is still being debated, it is generally acknowledged that the systems have a role to play in drinking water treatment. Certified systems being marketed today incorporate proven technologies that have been engineered to achieve defined contaminant-removal targets. Although this is of paramount importance, there is value in assessing the sustainability of such treatment alternatives. This article investigates issues related to the implementation, management, and environmental effects of POU/POE systems and presents a framework for sustainability assessment of POU/POE systems. A set of sustainability criteria—technical, economic, environmental, and sociocultural—is defined. Quantitative and qualitative indicators are proposed to promote the practical use of these criteria to compare and select among POU/POE systems. Survey results of experts’ judgment on the effectiveness of the developed indicators are presented.

Keywords: point-of-use, point-of-entry, sustainability, water treatment, indicators

3.1 Introduction

The framework on integrated water resources management (IWRM) represents a paradigm shift in how water systems are perceived and what to expect from management practices. IWRM is defined as "a process which promotes the coordinated development and management of water, land, and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP, 2000). This vision of IWRM includes the promotion of water system sustainability. Therefore sustainability should be applied regardless of the scale of water treatment, including comparing alternatives to select that which is more sustainable.

Nontraditional water supply systems have entered the water supply arena (Raucher *et al.*, 2004; Cotruvo and Cotruvo, 2003). As with most nontraditional methods, these systems often evoke contradictory opinions and perceptions from stakeholders in water supply—ranging from total rejection to a recommendation for their implementation. Of these nontraditional alternatives, point-of-use (POU) and point-of-entry (POE) systems has been the focus of many studies and investigations, primarily on their capabilities to assist in complying with water regulations. However, the sustainability of such systems still needs investigation. Sustainability is often described as having three main components: environmental protection, social well-being, and economic well-being. The objective is to strike a balance when using resources in such a way that the contribution to local and global problems is minimized or at least known and accounted for.

The growing interest in POU/POE units has led to increased numbers of commercial units being marketed as potential solutions to real or perceived water problems that are often aesthetic in nature. This leaves community water suppliers with the difficult task of choosing among these units. Many of these units go through rigorous testing procedures to ensure their proper functioning, and units that pass these tests become "certified." A POU/POE system is typically a "treatment train"—a number of treatment processes arranged in series or in parallel to treat the influent water to the target water quality. POU/POE treatment trains can either be an integrated off-the-shelf product or an assembled line of individual products.

An increasingly relevant question is whether centralized (municipal) systems are the most sustainable form of water treatment or whether in certain situations it may be advantageous to implement or switch to decentralized and POU/POE systems. However, to answer this question, investigations of the sustainability of different POU/POE systems need to be conducted.

This study does not investigate the feasibility and sustainability of POU/POE water treatment as an alternative to central water treatment for particular applications. Although this investigation has global implications, it has been prepared from the perspective of how to proceed after the decision is made to use a POU or POE system to assist North American water purveyors and consultants in selecting the most suitable system. The aspects of sustainability for which a particular POU/POE system should be assessed before being implemented are investigated. Only certified POU/POE units are considered. In addition, this investigation focuses on setting a framework for comparing and selecting among the different POU/POE alternatives on the basis of sustainability. The work presented here is the basis for a user-friendly decision support system that is being developed.

3.2 POU/POE Water Treatment

Recent POU/POE technologies offer a range of alternatives to replace or complement central water treatment in certain situations. POU/POE units are designed to reduce specific contaminants in drinking water, including heavy metals, pesticides, particulates, and pathogens (Chaidez and Gerba, 2004). POU/POE systems can be effective in removing or inactivating waterborne pathogenic bacteria, viruses, and protozoa if they are properly designed, engineered, operated, and maintained (Abbaszadegan *et al.*, 1997). Most treatment technologies can be implemented on a POU/POE scale, including activated carbon, distillation, membrane filtration, and ultraviolet disinfection. Regulation 170/03 of the Ontario Safe Drinking Water Act defines a POE system as one that provides primary disinfection (but no chlorination), is installed at or near where water enters a building, and is connected to the plumbing (OMOE, 2002). NSF/ANSI standards add that flow of a POE system should be >15 L/min (4 gal/min) at a 103-kPa (15-psi) pressure drop and 18±5°C (64.4±9°F) temperature (NSF/ANSI Standard 53, 2007). A POU system, on the other hand, is installed at or near where water is directly used and may or may not be connected to plumbing.

The most important factor in the rising use of POU/POE treatment is increased consumer awareness about water issues, including aesthetic considerations and perceptions about the safety of centrally treated water. Studies show that a considerable number of consumers in North America have concerns about water safety (Dupont, 2005; Jones, 2005; Turgeon *et al.*, 2004; Odoi *et al.*, 2003). Taste-and-odor issues are often the causes of consumer concern; a survey reported 66% of adults in the United States were worried about their water's aesthetic quality and that 41% used POU/POE treatment units in their homes (WQA, 2001). Concerns are exacerbated when water originates from a private source; a survey of a Canadian community showed that 56% of respondents used in-home treatment to polish water from their wells (Jones *et al.*, 2006).

There has also been an interest in POU/POE systems as a means of reducing risk and providing a sense of security. POU/POE systems have been advocated as being an appropriate final barrier in the multibarrier approach to drinking water treatment (McEncroe, 2007; Lykins *et al.*, 1995). They may provide protection from microbial and chemical contaminants entering a distribution system as a result of cross connections, backflow, equipment failure (pumps, pipes), accidental damage (excavating, landscaping), unacceptable installations (those in or near septic tanks, tile fields, or subsoil treatment systems), chemical dosing problems (fluoride, disinfectants), disinfection by-products (trihalomethanes), corrosion or leaching from water-contacting surfaces (copper, aluminum, lead), reservoir management practices, reservoir contamination by wildlife, or even intentional introduction (exploiting these vulnerabilities or devising new opportunities) (USEPA, 2006a; Smith *et al.*, 2001; Srinivasan *et al.*, 1999; Williams *et al.*, 1997).

POU/POE units have also been proposed as a direct water treatment alternative for small, rural, or remote communities, especially where groundwater is the source (Anderson and Sakaji, 2007; McEncroe, 2007; Cotruvo and Cotruvo, 2003; Kuennen *et al.*, 1992). In this case, the systems are more complex than devices certified for use with treated water, and the level of control and monitoring required for these units is far stricter. POU/POE devices represent an alternative for small water systems with limited financial resources and expertise to comply with increasingly strict regulations (Jones and Joy, 2006). Furthermore, small and rural water systems are distributed by nature when homes are too far apart to be connected with water networks, making a decentralized or distributed water treatment system more feasible.

Research and scientific advances in attribution of health implications of the existence of certain compounds in drinking water and improvements in detection capabilities have led to the lowering of the maximum acceptable concentration of known compounds (e.g., arsenic, lead) and the introduction of new contaminants to regulations (e.g., methyl tert-butyl ether). Municipalities may modify water treatment plants, build new ones to comply with new standards, or potentially adopt a decentralized water treatment strategy in which some contaminants can be removed at the small or POU level (Jones and Joy, 2006; Cotruvo and Cotruvo, 2003). The choice is to some extent based on a comparative benefit analysis governed by the cost of each alternative.

3.3 POU/POE Governance and Management

When it comes to using POU or POE water treatment to satisfy drinking water safety standards, six main entities are important to include when implementing such treatment systems:

Government monitoring agency. In Canada, the overseeing agency that ensures that the POU/POE implementation strategy functions properly is either the provincial Ministry of Health or the ministry responsible for the drinking water provision. In the United States, this agency is the US Environmental Protection Agency (USEPA); however, states may assume primacy by promulgating regulations that are at least as strict as those of the USEPA and optionally even more restrictive.

Water purveyor (municipality or private company). This is the entity responsible for the operational plan for implementing POU/POE treatment systems on a local scale.

POU/POE systems supplier/manufacturer associations. In North America these are the Water Quality Association (WQA) and the Canadian Water Quality Association, which are not-for-profit trade associations representing the residential, commercial, industrial, and small community water treatment industries. They represent suppliers and provide guidance on product marketing and performance claims.

Independent certification organization. Standards are developed to test drinking water treatment systems, their components, and the materials used in them to ensure that they meet the minimum requirements for performance (mainly contaminant-reduction claims) and structural integrity from plumbing, electrical, mechanical, and material toxicity perspectives. NSF is the organization responsible for developing such standards in North America under ANSI. In addition to NSF, other entities test and certify the units to NSF/ ANSI standards.

Water associations. These organizations (which may include those also playing an advocacy role) promote research and consumer awareness regarding water treatment alternatives and the strategies and responsibilities they entail (e.g., AWWA, Canadian Water and Wastewater Association, Safe Drinking Water Foundation).

Consumer organizations. Representing consumer concerns and interests, these organizations are responsible for consumer awareness regarding new strategies and the responsibilities they entail. They can also be water supply cooperatives delivering drinking water to communities. Some of these entities play a limited role in the POU/POE industry, but it is envisioned that their involvement will increase.

Regulatory agencies have traditionally adopted a stronger position against POU treatment devices than POE systems. However, a closer look at the timeline in Figure 3.1, which depicts the changes in positions toward POU/ POE systems, shows that there has been a gradual shift in the consideration of POU/POE systems in regulations (Figure 3.1, part A). Several water regulations have included acceptance of POU/ POE treatment as an alternative to comply with maximum contaminant levels, including the following:

1. US Safe Drinking Water Act, section 1412(b)(4) (E)(ii), instructs the USEPA to include POU/POE systems in the list of technology alternatives to achieve compliance with maximum contaminant levels for small water systems (serving a population <10,000). This section sets a limit on using POU units by prohibiting their use to achieve compliance with a maximum contaminant level or treatment technique requirement for a microbial contaminant (or an indicator of a microbial contaminant).
2. The Ontario Safe Drinking Water Act Regulation 170/03 (Drinking water Systems) Schedule 3 identifies POE as compliance technology for small municipal residential systems (defined as systems serving fewer than 101 private residences).
3. The British Columbia Drinking Water Protection Act (DWPA), section 3.1, stipulates that a small water system in which each recipient of the water has POE or POU treatment that makes the water potable is exempt from section 6 of the DWPA (which requires a water supply system to provide potable water; BCMOH, 2003). It is notable that, of the few reviewed regulations, the British Columbia DWPA is the only regulation that does not set limitations on the use of POU units for compliance.

In response to the increased adoption of POU/POE treatment units in 1968, NSF was assigned the task of developing certification standards under ANSI. However, there is more than one entity that can certify units to these standards, including the WQA, the Canadian Standards Association International, Underwriters Laboratories, the Quality Auditing Institute, and the International Association of Plumbing and Mechanical Officials. The evolution of NSF standards over the past few decades is shown in Figure 3.1 (part B) and Table 3.1. NSF certification requires a POU/POE water treatment unit to meet the following requirements:

1. Contaminant reduction claim(s) must be verified.
2. Materials and components of the system must not add anything harmful to the water.

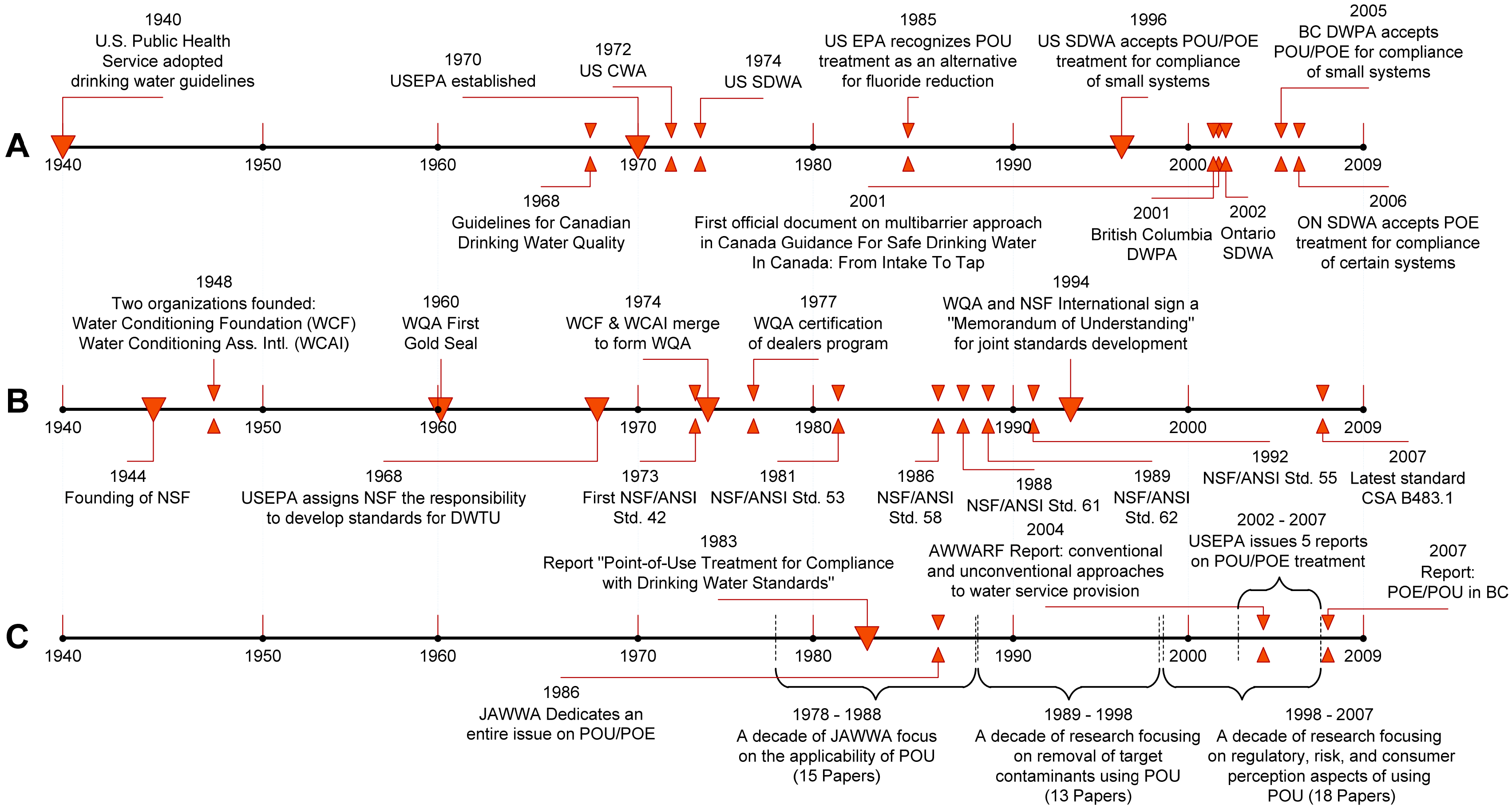

Figure 3.1 Timeline for the evolution of governance and management practice of POU/POE water treatment (A) regulatory, (B) certification and industry, and (C) research

Where: BC—British Columbia, CSA—Canadian Standards Association, CWA—Clean Water Act, DWPA—Drinking Water Protection Act, DWTU—drinking water treatment unit, JAWWA—Journal AWWA, ON—Ontario, POE—point of entry, POU—point of use, SDWA—Safe Drinking Water Act, USEPA—US Environmental Protection Agency, WACI—Water Conditioning Association International, WCF—Water Conditioning Foundation, WQA—Water Quality Association

3. The system must be structurally sound.

4. The advertising, literature, and product labeling must not be misleading.

5. The materials and manufacturing processes used cannot change without recertification.

Table 3.1 POU and POE treatment unit certification standards

Standard	Title	POE	POU
NSF/ANSI 42	Drinking water treatment units—aesthetic effects	Yes	Yes
NSF/ANSI 44	Residential cation exchange water softeners	Yes	No
NSF/ANSI 53	Drinking water treatment units—health effects	Yes	Yes
NSF/ANSI 55	Ultraviolet microbiological water treatment systems Class A: systems (40,000 μW-sec/cm^2)* designed to disinfect and/or remove microorganisms from contaminated water, including bacteria and viruses, to a safe level Class B: systems (16,000 μW-sec/cm^2)* designed for supplemental bactericidal treatment of public drinking water or other drinking water, which has been deemed acceptable by a local health agency	Yes	Yes
NSF/ANSI 58	Reverse osmosis drinking water treatment systems	No	Yes
NSF/ANSI 60	Drinking water treatment chemicals—health effects	Yes	Yes
NSF/ANSI 61	Drinking water system components—health effects	Yes	Yes
NSF/ANSI 62	Drinking water distillation systems	Yes	Yes
NSF/ANSI 177	Shower filtration systems—aesthetic effects	No	Yes
NSF/ANSI P231	Microbiological water purifiers	Yes	Yes

*40,000 μW-sec/cm^2 = 40 mJ/cm^2; 16,000 μW-sec/cm^2 = 16 mJ/cm^2

Although research started only a decade after NSF and WQA efforts to coordinate and manage the industry, it may have helped in the acceptance of POU/POE systems for compliance with regulations (Figure 3.1, part C). The time line of research activities on POU/POE shows that sustainability-focused investigations of these treatment methods are timely.

3.4 Sustainability Concerns with POU/POE Treatment

There are several sustainability concerns regarding the implementation of POU/POE systems outlined in reports and research studies.

- Logistical challenges are typical of all decentralized systems—and POU/POE systems are decentralized systems that demand the distribution of responsibilities among stakeholders. Although regulations assign most of the responsibilities to water service providers, educating all interested stakeholders on their roles and responsibilities is a crucial factor for the success of POU/POE treatment systems (USEPA, 2002).
- Stakeholder involvement is important for POU/ POE systems' decision-making processes. Substantial involvement is needed to deliver water systems that users "buy into."
- Risk of failure either from improper operation or unit malfunction in POU/POE systems can have serious health implications (Anderson and Sakaji, 2007). Moreover, units vary considerably in their efficiency and operation and maintenance requirements. Thus such systems may require trained operators and maintenance personnel, who may or may not be available, despite the fact that the equipment is fairly simple to operate and maintain.
- The costs of implementing POU/POE treatment systems vary depending on the level of treatment and the quantity of water treated (USEPA, 2007; Craun and Goodrich, 1999).
- There is a lack of information about how to choose among a multiplicity of units, given the limited scope of POU/POE certification programs (Craun and Goodrich, 1999). The selection process requires often unavailable information of a unit's components, life cycle, operation and maintenance requirements, and generated residuals. However, depending on the technology incorporated in a POU/POE unit, the expected performance and removal efficiency of the unit can be estimated.
- The market growth of POU/POE units is overwhelming. Worldwide, there are about 380 manufacturers of certified POU/POE units listed by NSF, producing ~5,700 drinking water treatment products. Only 2,356 of these products are treatment units; the remaining products are accessories and replacement elements such as faucets, filter cartridges, housing adapters, membranes, valves, pumps, and tanks. There are varying configurations of POU units available on NSF's list of certified treatment units (NSF, 2008). Figure 3.2 shows that certified plumbed-in units represent ~75% of total certified products. In 1999, a

survey of drinking water units in Canada revealed that certified products account for only 34% of the POU/POE market (Lavoie, 2000).

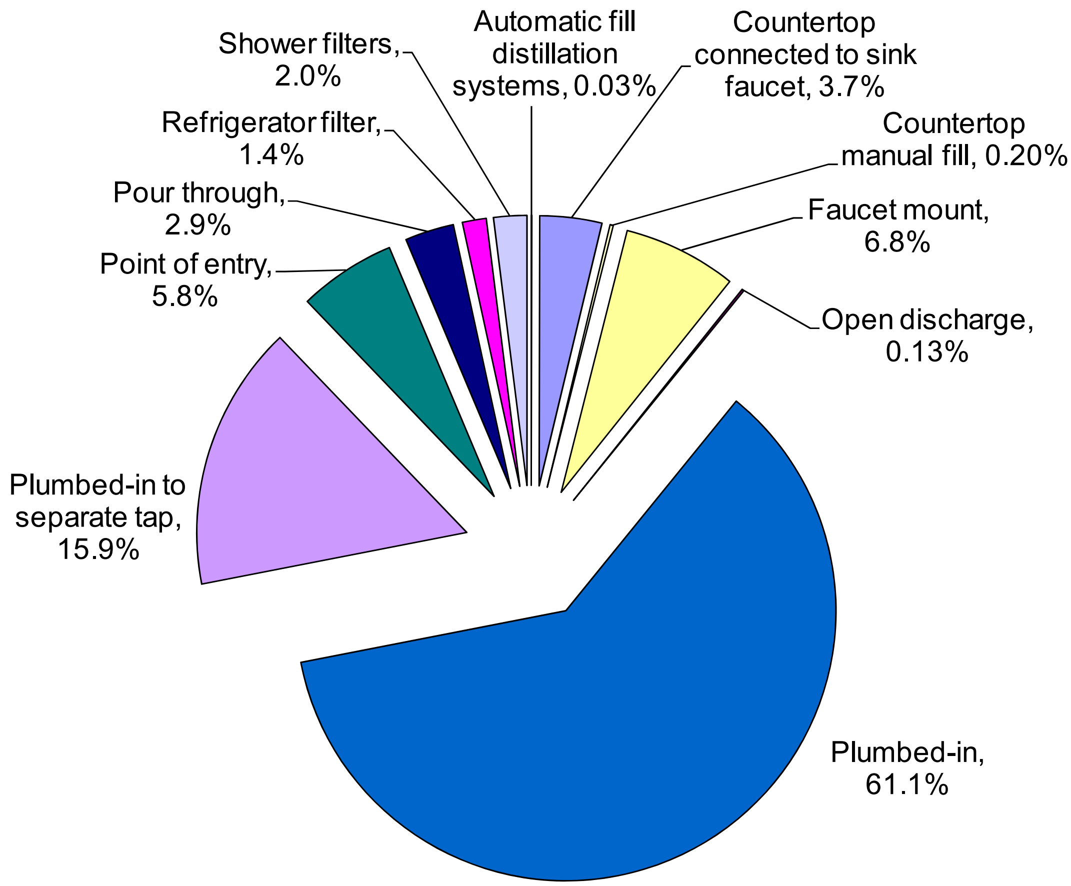

Figure 3.2 Percentage distribution of water treatment units' configurations certified to NSF/ANSI standards (as of Apr. 19, 2009)

- Waste management plans should be designed to dispose of systems' spent cartridges, media, membranes, bulbs, and filters at the end of their useful life. In addition, waste brines from POU and POE reverse osmosis systems and POE ion-exchange systems and backwash from POE-activated alumina and granular activated carbon systems must also be disposed of (USEPA, 2002). Therefore, before selecting a treatment technology, the potential difficulties associated with the disposal of these wastes must be considered.

3.5 A Framework for Sustainability Assessment of POU/POE Systems

The difficulties that water service providers may face when selecting POU/POE systems, particularly with regard to sustainability considerations, should also be considered. The proposed framework is intended to be part of an integrated process that analyzes and suggests POU and POE water treatment systems as potential sustainable water treatment alternatives for a particular water source. The framework serves as a decision-aid tool to reduce the treatment alternatives based on the characteristics of the case under analysis. Objectives of sustainability vary depending on the context. In this case, for a water system to be sustainable; it has to strive to achieve a nontoxic environment; have no negative effect on human health and hygiene; provide a better use of human, natural, and financial resources; have a high degree of functional robustness and flexibility; and ensure cultural acceptance, thus encouraging responsible behavior by its users (Hellstrom *et al.*, 2000).

In the past decade, the engineering approach to sustainability has shifted from its earlier general focus of minimizing negative effects to effectively incorporating sustainability in development and planning before implementation. Some studies have focused on an energy-efficiency viewpoint in which the assessment was done simply by calculating the amount of treated water in kilograms produced per kilowatt of supplied energy (Afgan *et al.*, 1999). Other approaches include the use of life-cycle assessment, practical minimum energy requirements, whole-life costing, and ecologic footprinting (Ashley *et al.*, 2008). However, perhaps the most common technique is to define new sets of criteria that represent a departure from a traditional cost-effectiveness approach to a more comprehensive sustainability approach.

Choosing among a variety of treatment alternatives is generally based on the constraints posed by both the objectives and the characteristics of the treatment operation. For the choice to be sustainable, the selection or decision-making process itself has to incorporate a sustainability aspect (Starkl and Brunner, 2004). Researchers and designers refer to the factors that help in selecting a treatment alternative as criteria, factors, or parameters. These criteria are usually hard to assess or measure, which leads researchers to use sets of proxy indicators, variables, constraints, or functions that best assess the criteria. The proposed framework provides a process to select sustainable POU/POE treatment trains that comprises the five stages outlined in Figure 3.3 and is explained in the following paragraphs.

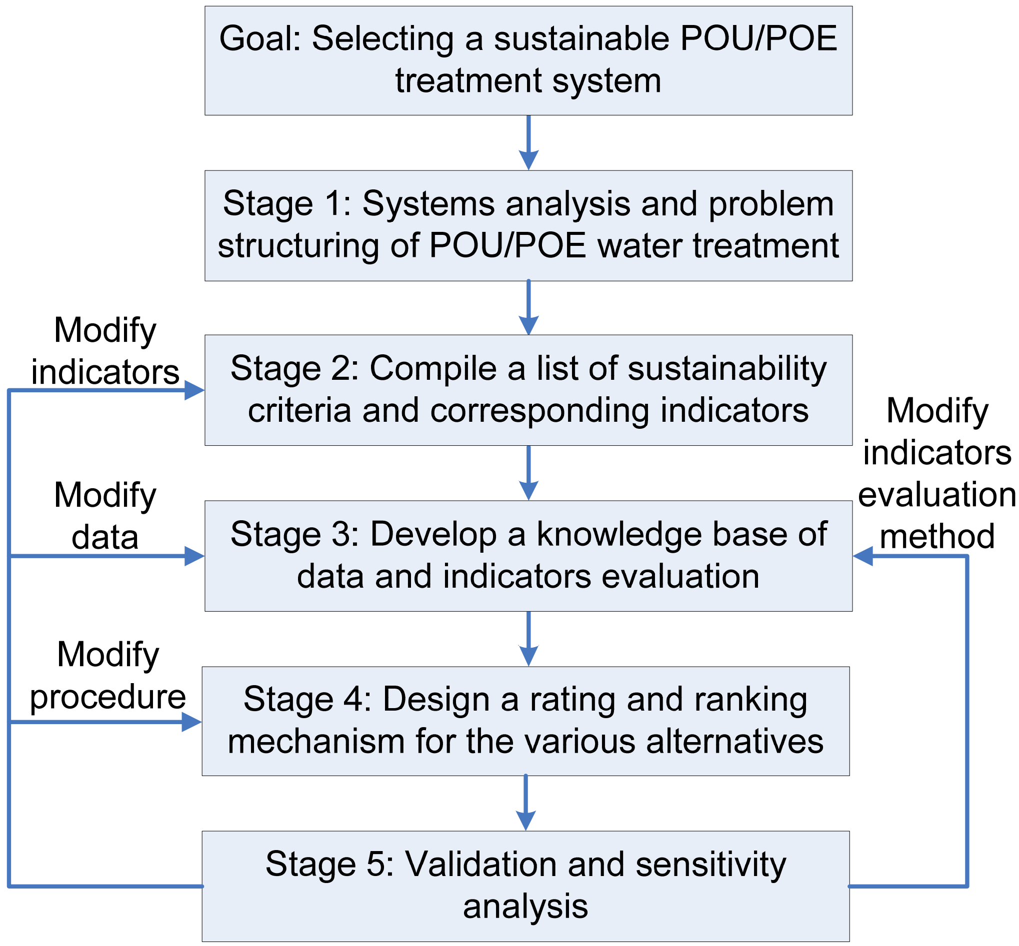

Figure 3.3 A framework for selecting sustainable POU/POE water treatment systems

Stage 1. Systems analysis and problem structuring involve identifying stakeholders in POU/POE water treatment and their interests, the definition of issues, and the identification of objectives (Flores *et al.*, 2007). The analysis is translated into preferences and constraints of various POU/POE alternatives and is coded into the process of selecting sustainable treatment systems. For example, a technical constraint can be triggered when the feedwater has a high chlorine content, which rules out reverse osmosis membranes that have no prefilters. The advantage of using the systems analysis approach is that it accounts for the multidimensional aspects of sustainability (Hamouda *et al.*, 2009). Figure 3.4 outlines relevant information needed in selecting a POU/POE system. Ideally, all relevant information should be considered in the developed selection framework; however, this may not be attainable because of a lack of data.

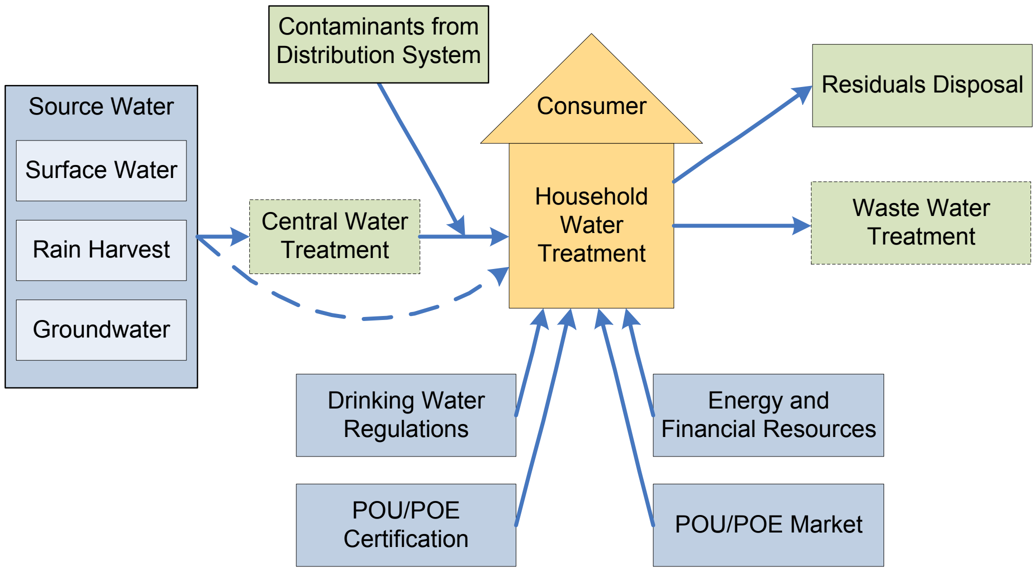

Figure 3.4 Scope for the systems analysis for POU/POE sustainability assessment

Stage 2. Sustainability criteria are defined as factors that may be used to assess which of a range of POU/ POE treatment trains offers the greatest contribution to achieving sustainability objectives. To increase the comparability among different alternatives, indicators are used to convert data into knowledge that can evaluate performance against the sustainability criteria. The main difficulty in using this approach is that different stakeholders will devise different criteria. It is difficult to have stakeholders buy into using predefined criteria and indicators to select among the POU/POE treatment trains. A compromise is to let stakeholders decide on the criteria/indicators and their relative importance. Stakeholder involvement can be accomplished through structured interviews, questionnaires, or focus groups. This way, the developed list of criteria and indicators can be applicable to all situations in which POU/POE systems are being considered.

Stage 3. POU/POE certification lists are valuable in setting up a database of the available units and their treatment claims, which can help in selecting suitable treatment systems tailored to remove target contaminants. However, developing the POU/POE knowledge base for use in the selection process will require further investigation in order to include other nontechnical aspects of sustainability for each treatment unit. Furthermore, treatment trains rather than individual treatment units need to be considered in the comprehensive framework of the selection process. In the course of selecting among treatment alternatives, the first step is to prepare predefined common treatment trains, such as that shown in Figure 3.5. These trains take into consideration restrictions associated with sequencing treatment processes.

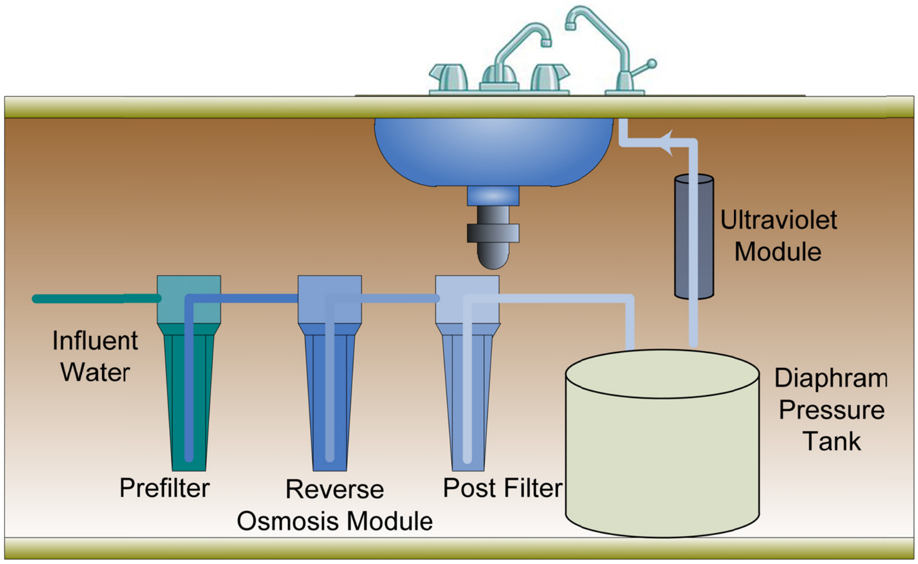

Figure 3.5 Sample schematic of a point-of-use reverse osmosis treatment train

The knowledge base can include: (1) treatment unit type and description, (2) reduction claims and target contaminants, (3) incidental effects (e.g., other contaminants removed, variation in pH), (4) maximum and minimum flow, (5) conditions that increase/decrease efficiency (e.g., presence of a specific contaminant that impedes the efficient performance of the device), (6) service life, and (7) a document that includes installation instructions, including required permits for construction, operation, and pilot-study and water-quality monitoring and reporting procedures.

Stage 4. To encompass all aspects of a POU/POE treatment system and properly assess its sustainability, the decision-maker is left with a set of indicators that has disparate and incompatible units of measurements. To avoid comparing a large number of treatment alternatives, constraints can be used to screen out nonfeasible alternatives. A screening algorithm can be developed by superimposing known case-specific constraints. The constraints used can be user-defined (e.g., eliminating POU treatment as an alternative and focusing on POE in a particular situation) or a technology characteristic. These technical constraints include limits on the influent turbidity, influent hardness, and influent pH.

After screening out infeasible alternatives, the remaining alternative systems can be rated and ranked according to their fulfillment of sustainability objectives. The most common approach to rate and rank alternatives is to follow a multi-criteria decision analysis (MCDA) (Lai *et al.*, 2008). The simplest form of MCDA is to quantify the evaluation criteria and calculate the weighted sum score for each alternative. An MCDA can become more complex when there are conflicting objectives and limiting constraints. The objective is to rank a large number of systems according to sustainability ratings. A range of MCDA methods can be used in ranking alternatives. It can be done through a pairwise comparison of alternatives using an analytical hierarchy process or other methods such as ELECTRE (Elimination Et Choix Traduisant la Realité [elimination and choice expressing reality]), simple multiattribute rating technique (SMART), or Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE); these methods have been reviewed elsewhere (Hamouda *et al.*, 2009; Ashley *et al.*, 2008; Lai *et al.*, 2008). The selection framework output will rank the more sustainable systems recommended for implementation from the alternatives knowledge base.

Stage 5. A sensitivity analysis is needed to validate the implemented sustainability-assessment framework. Sensitivity assesses the change in the outcome of the framework as affected by the tradeoffs made by choosing different technologies, different technology combinations, or different weights on the sustainability indicators. The results of the sensitivity analysis will help improve the framework through a feedback loop that highlights aspects that need change or improvement (e.g., improving data quality, changing an indicator or its evaluation method, changing the entire sustainability-rating procedure; Figure 3.3). The following section describes one of the cornerstones of the sustainability assessment framework, which is to determine the criteria to be used in the assessment.

3.6 Sustainability Criteria and Indicators

Sustainability in water and wastewater management has been studied by many researchers, either through comparing various technologies in terms of sustainability or by outlining approaches for selecting sustainable solutions (Sahely *et al.*, 2005; Balkema *et al.*, 2002; Hellstrom *et al.*, 2000; Lundin *et al.*, 1999; Mels *et al.*, 1999; Otterpohl *et al.*, 1997). Several studies have established indicator sets for sustainable water and wastewater treatment (Table 3.2). The classification of indicators shown in Table 3.2 differs from one study to another. Nevertheless, most sets include health-related, environmental, economic, sociocultural, and technical criteria.

The traditional framework for sustainability assessment translates the demands of the end user (consumer, government, or organization) into functional criteria that must be fulfilled by the technology. This framework does not claim that the selected alternative is the optimum or best alternative; rather, it claims that the selected alternative is the highest ranking when evaluated by a defined set of criteria (Ashley *et al.*, 2008). The multiplicity of criteria and indicators being developed in the field of water and wastewater treatment shows the importance of focusing on a conceptual basis for sustainability assessment. In theory, criteria and their respective set of indicators should reflect the sustainability issues of the problem at hand. The aggregation function for the indicators' categories forms clusters of indicators, which in turn are the components of a sustainability index that represents a rating of the system (Afgan, 2008).

Table 3.2 List of indicators used in select studies for sustainable treatment alternatives

Indicator	Description	Unit	Reference
Technical			
Removal efficiency	Treatment modules' removal efficiency score (%) for a spectrum of water contaminants	QN	(Ahmed *et al.*, 2003)
Environmental impact	Scoring is based on deviations of effluent from the regulatory standards	QN	(Heller *et al.*, 1998)
Pollutants removal	Removal of nitrogenous and phosphorous pollutants	QL	(Zeng *et al.*, 2007)
Performance efficiency	Fuzzified with user preference membership function	QL	(Yang and Kao, 1996)
Reduction of pollutants	Based on the quality of reduction, and number of pollutants removed	NS	(Wukovits *et al.*, 2003)
Treatability	Confidence curves for treating a compound by a technology	QN	(Krovvidy, 1998)
Flexibility/ adaptability	Flexibility to implement on different scales, capacities, and changes in legislation	QL	(Balkema *et al.*, 2002)
Reliability	Sensitivity of the process with respect to malfunctioning equipment and instrumentation	QL	(Balkema *et al.*, 2002)
Robustness	Sensitivity of the process with respect to toxic contaminants, shock loads, seasonal effects	QL	(Balkema *et al.*, 2002)
Operational complexity	Score is based on the total number of permeate and concentrate stages in the treatment design	QL	(Heller *et al.*, 1998)
Professional skills for O&M	This index stands for the automation level of the treatment plant	QL	(Zeng *et al.*, 2007)

Indicator	Description	Unit	Reference
Economic			
System cost	The total system costs are composed of the capital costs and operation and maintenance costs	QN	(Heller *et al.*, 1998)
Operating cost	Includes effluent fines and costs of aeration, pumping, sludge disposal, chemicals, and mixing	QN	(Flores *et al.*, 2007)
Cost	Denoted by capital present value of capital costs and all the costs during the operation period	QN	(Zeng *et al.*, 2007)
	Cost functions for each treatment module in terms flow based on prevailing local expenses	QN	(Ahmed *et al.*, 2003)
Construction cost	Estimated using a model; includes unit costs (excavation, concrete, etc.), equipment, and labor	QN	(Flores *et al.*, 2007)
	Cost functions describe the cost of constructing a unit process for a given flow rate	QN	(Krovvidy *et al.*, 1991)
Land area	Obtained by quantitative comparison according to construction records (in square meters)	QN	(Zeng *et al.*, 2007)
Floor Space	Score is based on the total number of permeate and concentrate stages in the treatment design	QL	(Heller *et al.*, 1998)
Environmental			
Energy use	Energy used by treatment	QN	(Balkema *et al.*, 2002)
Energy balance	Results of energy usage and recovery from sludge digestion	QN	(Mels *et al.*, 1999)
Socio-cultural			
Cultural acceptance	Indication of convenience and correspondence with local ethics	QL	(Balkema *et al.*, 2002)
Institutional requirements	Indication of efforts needed to control and enforce existing regulations	QL	(Balkema *et al.*, 2002)
Availability	Indication of technology, chemicals, and accessories availability	QL	(Chowdhury and Husain, 2006)
Expertise	Indication whether a system can be designed and built locally or by specialized manufacturers	QL	(Balkema *et al.*, 2002)

QL-Qualitative assessment, QN-Quantitative assessment, NS-Not specified, O&M-Operation & Maintenance

A proper indicator has to use quantifiable, reliable data to assess any aspect of sustainability. The aggregation of indicators depends on the ultimate goal of the sustainability assessment. In our case, the goal is to select among different alternatives; therefore, comparability is a key feature of the designed sustainability assessment scheme. It is clear from Table 3.2 that most technical and economic indicators are similar, whereas the views about environmental and social indicators are different. Even for similar factors, the assessment method may differ. For example, when evaluating the environmental merit of an alternative, some researchers assess quantitative indicators such as energy use (Balkema *et al.*, 2002; Mels *et al.*, 1999), whereas others are more interested in a qualitative judgment of environmental friendliness.

3.6.1 Sustainability Criteria for Selecting among POU/POE Systems

POU/POE treatment systems need their own sustainability criteria to assess alternatives. A tentative list of the sustainability criteria, underlying objectives, and proposed indicators to be used in assessing sustainability is shown in Figure 3.6. The criteria used to rate various systems include: (1) technical criteria, which define the technical performance, implementability, and operability of an alternative; (2) economic criteria, which can be a constraint when choosing a particular treatment train (including purchase and installation costs and operation and maintenance costs); (3) environmental criteria, which are often overlooked on such a small scale (nevertheless, the environmental effect can be evaluated by assessing resource use and possible residuals resulting from the treatment train); and (4) sociocultural and institutional criteria, which are rarely considered in sustainability assessment of water treatment processes; however, because they play an important role, indirect measures of consumer acceptability and availability of products can be used.

The developed indicators can be used to assess the sustainability of treatment trains. The treatment train is defined by the type and number of processes. However, before applying these indicators, their effectiveness and the extent to which they include the various sustainability issues must be examined. Because several of the indicators proposed in this framework were developed by the author, it was necessary to validate indicator effectiveness. A questionnaire was designed to obtain feedback and develop consensus on the final list of indicators. Fifteen experts in water treatment and particularly POU/POE systems were approached. Eleven responded, generating 52 comments. The experts were employees of consulting firms, NSF, WQA, and Underwriters Laboratory Inc.; professors specializing in water research; municipal water providers; employees or former employees of Canadian Standards Association International; and those from Canadian federal or provincial departments or ministries involved with the provision of drinking water. The questionnaire was not designed to allow extensive statistical analysis of the results, but to evoke a discussion of the proposed indicators.

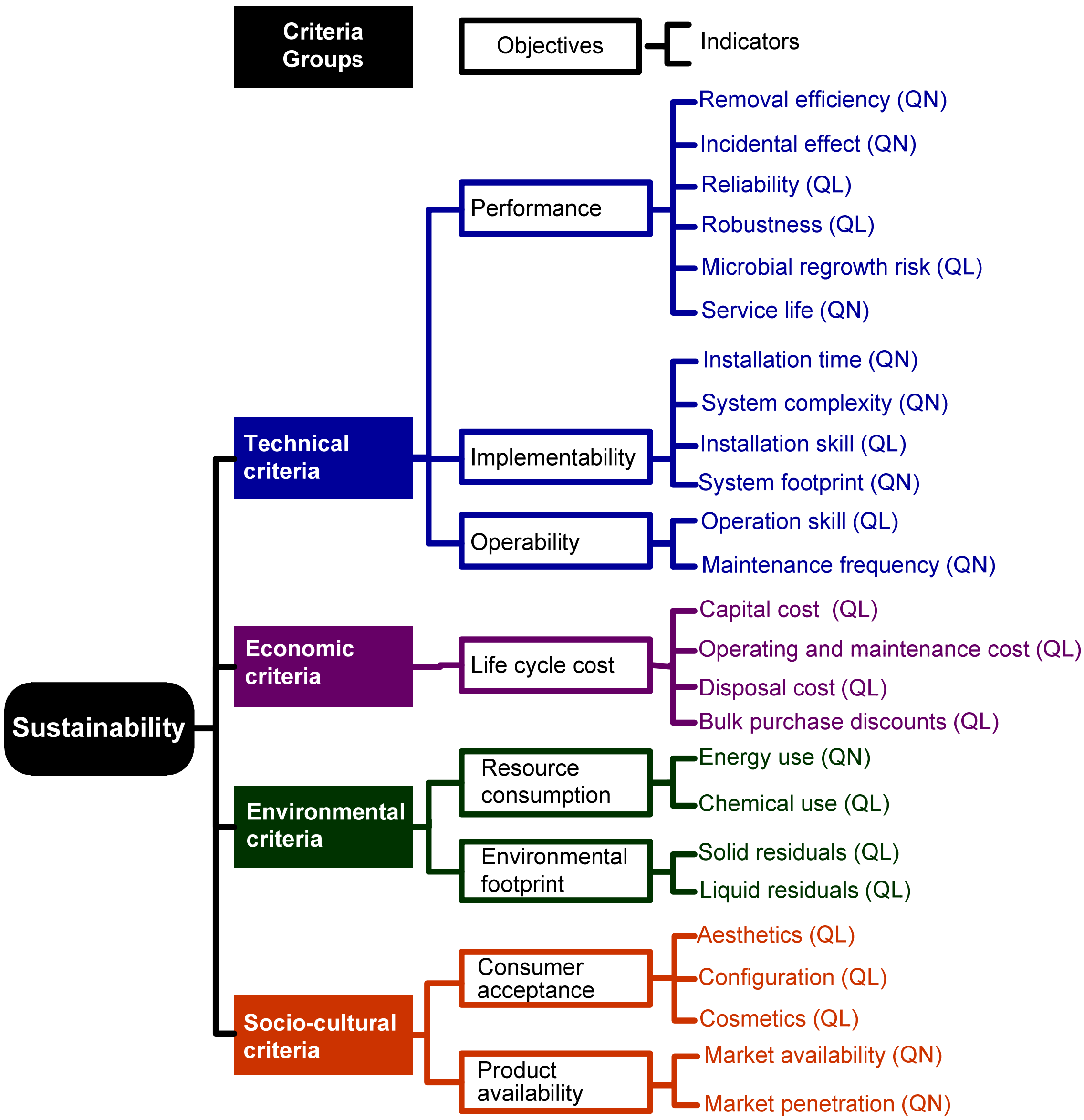

Figure 3.6 Proposed list of indicators to assess the sustainability of alternative POU/POE treatment systems
QL—qualitative assessment, QN—quantitative assessment

3.6.2 Sustainability Indicators Discussions

Figure 3.7 provides a summary of the experts' judgments on the effectiveness and appropriateness of the developed indicators. Most of the indicators were thought to be important by more than 50% of the respondents. Although this implies that the developed indicators were well received by the experts, the 50% acceptance rate alone should not be used to decide on whether to use these indicators. The experts' comments contributed to the decision to remove, modify, or adopt a particular indicator. Nevertheless, Figure 3.7 suggests that indicators such as incidental effect, microbial regrowth risk, installation time, system complexity, and bulk purchase discount should be revisited to assess their relevance and effectiveness because fewer than 50% of the experts thought of them as effective indicators. However, the relatively high or low level of support for some of these indicators may be related to the makeup of the expert panel. Each decision-making entity (utility or regulatory agency) that uses the selection framework should consider assigning relative weights based on their local situations or values.

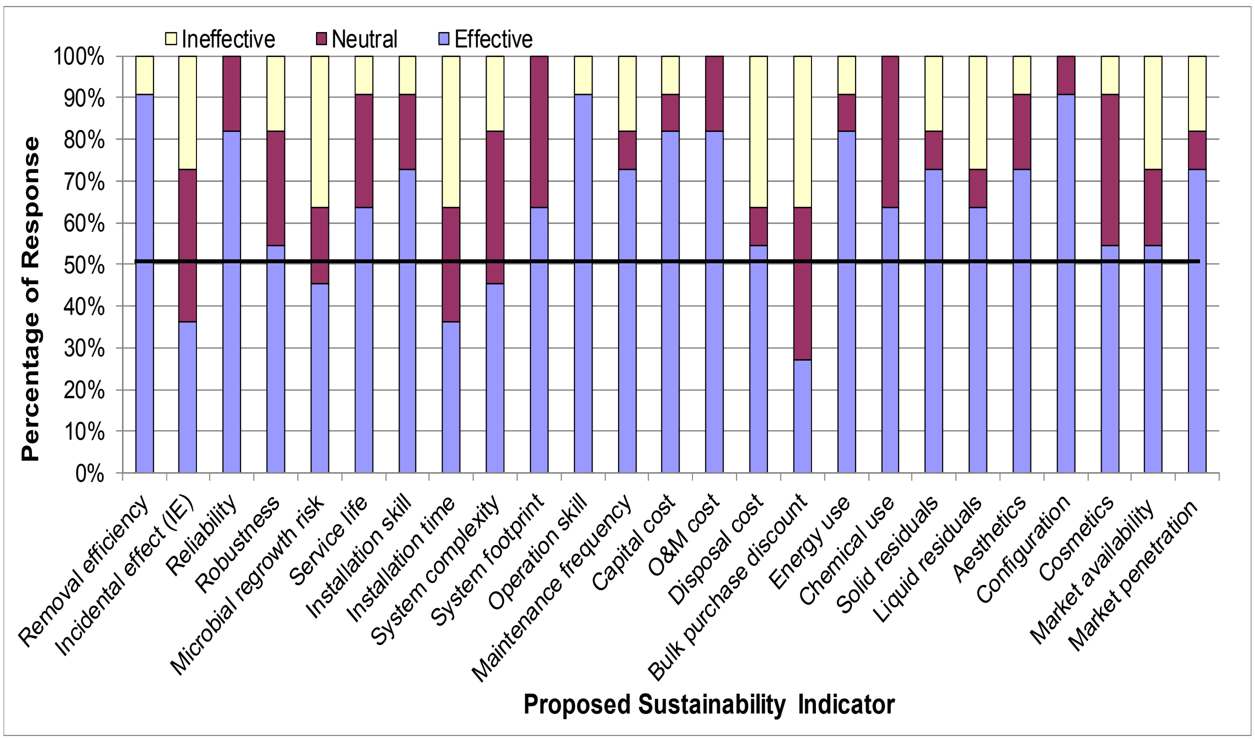

Figure 3.7 Experts' opinions on the effectiveness of the proposed POU/POE indicators in assessing sustainability

Technical indicators. There was little disagreement among the respondents on the importance of technical indicators, and removal efficiency remained the top technical concern (Table 3.3, Figure 3.7). The incidental effect indicator was considered by some respondents to be of low importance because a system is usually selected to remove a target contaminant. However, it can be argued that, all indicators being equal among competing products, the ability of a treatment system to remove additional contaminants is important. This applies in situations in which some contaminants can potentially remain undetected or in which there is a desire to protect against the risk of intentional introduction.

Table 3.3 Description of technical sustainability indicators and methods of evaluation

	Indicator	**Description**
Performance	Removal efficiency	Reduction efficiency (%) of treatment train for target contaminant (chemical and microbial) as certified to NSF/ANSI standards
	Incidental effect (IE)	Additional removal of contaminants other than those targeted in the influent water, IE = $(C_t - C_w)/C_t$ (range 0 to 1) C_t : # contaminants removed by the train (as certified by NSF) (e.g. = 5) C_w : # target contaminants in influent water (e.g. = 3) e.g. IE = (5-3)/5 = 0.4
	Reliability	Sensitivity to malfunctioning Reliability = (Pt – 1)/Pt Pt : number of individual processes in train removing target contaminant e.g. a train having GAC and RO used to remove arsenic will have Reliability = (2-1)/2 = 0.5
	Robustness	A qualitative assessment of sensitivity of a treatment train concerning toxic contaminants, shock loads, and seasonal effects (rating of low, moderate, or high robustness)
	Microbial regrowth risk	An indication of the potential for increased heterotrophic bacteria (HPC), and the existence of a mitigation technique (rating of low moderate and high risk)
	Service life	Estimated service life until retirement in liters

	Indicator	Description
Implementability	Installation skill	A qualitative assessment of the level of skill required to install the train Low – installed by homeowner Moderate–unit distributer is required High – professional plumber and/or electrician required
	Installation time	Average time to install the train (hours)
	System complexity	A qualitative assessment of the complexity of a treatment train that considers the number of processes and accessories (rating of low, moderate, or high complexity)
	System footprint	Indication of average volume (or area) occupied by the train
Operability	Operation skill	A qualitative assessment of the level of skill required to operate the treatment train. Low – No formal training required Moderate – Training is useful High – Operator training required
	Maintenance frequency	Indication of frequency of maintenance required, expressed by: No. of maintenance hours / year + No. components to change / year

Comments by the respondents on other technical indicators included concerns regarding codependence. The installation time indicator was thought to be a dependent of installation skill; therefore, it was decided to remove it from the final list of indicators. System complexity seems to overlap with three indicators (operator skill, installation skill, and system footprint); therefore, it was removed from the list to avoid the risk of overemphasizing some factors over others. Other comments stemmed from a failure to acknowledge that indicators are developed considering all possible cases. The importance of a particular indicator in a given case is reflected in the weight that can be assigned to it. For example, there was an argument against the indicator of microbial regrowth risk based on the knowledge that such regrowth would be more risky to the immunocompromised than to otherwise healthy consumers. It was explained that whether an indicator is judged to be of importance (i.e., higher weight) will be dependent on the case (i.e., if the case includes a system intended to serve immunocompromised individuals, the indicator should be assigned a high weight, whereas if it is to serve healthy individuals it should have a low weight—perhaps even a weight of zero).

Economic indicators. Similar to technical indicators, there was consensus on the importance of economic indicators (Table 3.4). One comment suggested adding a dollar value to the indicators' assessment, which was done at each level of assessment (i.e., a low capital cost ranges from $0 to $50). Disposal cost was thought to be more appropriately included in the operation and maintenance cost category. Additionally, it was recommended that the bulk purchase discount indicator be linked to the number of systems to be installed.

Table 3.4 Description of economic sustainability indicators and methods of evaluation

	Indicator	**Description**
Life Cycle Cost	Capital cost	A qualitative assessment of the cost of purchase and installation (rating of low, moderate, or high)
	Operating and maintenance cost	A qualitative assessment of the operating and maintenance cost (rating of low, moderate, or high)
	Disposal cost	A qualitative assessment of the residuals disposal and decommissioning costs (rating of low, moderate, or high)
	Bulk purchase discount	A qualitative assessment of the potential discount on train bulk purchase (rating of low, moderate, or high)

Environmental indicators. The environmental indicators were well received because they also addressed safety issues, especially chemical use (Table 3.5). However, a perceived overlap between the energy-use indicator and the cost indicators was raised. Energy use is employed as an indicator of environmental effect, not cost. For instance, if lowering the environmental effect instead of the cost is the primary concern in a particular case, then although the economic indicators will be assigned low weights, the energy-use indicator will be assigned a high weight. In this case, the two indicators may be independent.

Table 3.5 Description of environmental sustainability indicators and methods of evaluation

	Indicator	Description
Resource Consumption	Energy use	Energy used by train per unit of treated water
	Chemical use	A qualitative assessment of chemicals used by train per unit of treated water. Low: chemicals used are of small quantity and mild or no impact Moderate: chemicals used are of larger quantity or of higher impact High: chemicals used are of larger quantity or of higher impact
Environmental Footprint	Solid residuals	A qualitative assessment of the treatment train production of solid waste per unit of treated water. Low: residuals can be disposed of in a standard solid waste management system, or the manufacturer provides a residuals collection system Moderate: residuals can be disposed of for a small cost High: residuals are hazardous and need special and costly treatment
	Liquid residuals	A qualitative assessment of the treatment train production of liquid waste per unit of treated water, rating is similar to that of solid residuals

Sociocultural indicators. The experts thought these indicators were of high importance, especially when dealing with a consumer who is not a water professional (Table 3.6). Nevertheless, concerns were raised about the ability to assess the indicators, especially those that require marketing data. Although a rigorous quantitative assessment of market factors can be very difficult and perhaps unjustified, the suggested assessment relies on a qualitative assessment to compensate for lack of data.

3.7 Conclusions

To enable decision-makers to choose sustainable POU/ POE water treatment systems, insights into the multidisciplinary nature of sustainability are needed. This necessitates the comparison between alternative treatment trains and units on technical, economic, environmental, and sociocultural grounds. Existing standards, reports, and guidelines provide knowledge to assist with selecting and implementing POU/POE systems. Nevertheless, they require expert interpretation, whereas marketing techniques are designed to appeal to consumers regardless of their knowledge, and in some cases the actual need for a supplementary device. It is important to rely on objective and professional resources when making an educated decision regarding which treatment system to use. This is a clear goal, especially in a marketing-intensive industry such as that of POU/POE devices, where advertising seems to dominate the decision-making process.

The framework proposed here provides a reliable approach for identifying sustainable treatment trains when provided with the various requirements and constraints for a specific case. The proposed framework will assist drinking water policy-makers, water purveyors, and consultants in selecting sustainable POU and POE treatment systems.

Table 3.6 Description of socio-cultural sustainability indicators and methods of evaluation

	Indicator	Description
Consumer Acceptance	**Aesthetics***	An indication of the aesthetic issues associated with water produced by the system, including issues such as warm or low pressure water (rating of low, moderate, or high aesthetic quality)
	Configuration	A rating of satisfaction with the system configuration: Under the sink, countertop, pitcher, etc. (rating of low, moderate, or high satisfaction)
	Cosmetics	An indication of the attractiveness and communication of the system with the user: 1. Decorative shape and color 2. Transparent vs. solid casing 3. Display of system performance (rating of low, moderate, or high attractiveness)
Product Availability	**Market availability**	A qualitative assessment of the market availability of a unit indicated by the coverage of the chain of stores in which it is sold (e.g. National chains, corner stores, or units sold online etc.)
	Market penetration	A quantitative assessment of the treatment train availability in the market expressed by the number of units certified to NSF/ANSI standards that fit the treatment train (e.g. # of certified units that fit the train prefilter-GAC-RO-UV)

* Assuming that the device functions properly (i.e. it passes performance indicators); taste, odor, and suspended particles should no longer be an aesthetic measure of the system; but are included in the system performance screening (i.e. if the source water has a taste and odor problem, only treatment systems that can remove taste and odor will be considered).

The process of developing the indicators helped to determine the important tenets of sustainability. The developed indicators strive to capture as many aspects of sustainability of POU/POE treatment as possible. The appropriateness of the indicators was investigated by soliciting experts' judgment and incorporating their comments into a refined list (Tables 3.3–3.6, with the system complexity and installation time indicators removed for reasons of redundancy).

The framework is to be further developed into an interactive, user-friendly, updatable decision support system to select sustainable certified POU/POE systems. Unlike the more complex sustainability assessment presented in this chapter, it is envisioned that the DSS will be sufficiently simple that it can be used by all stakeholders. The real test of the effectiveness of the developed indicators and the selection framework in capturing aspects of sustain-ability is to apply them to a real-world case study and to analyze the performance of the selected POU/POE treatment systems. Future research should reveal large gaps between the theoretical and practical aspirations of decision-making for the selection of sustainable POU/ POE treatment systems.

Chapter 4
Employing Multi-criteria Decision Analysis to Select Sustainable Point-of-Use Water Treatment Systems

This chapter is based on an article of the same title submitted for potential publication in a scientific journal on June 2011. Cited references are in the consolidated list of references at the end of thesis.

This article focuses on two tasks: (1) the indicator calculation methods; and (2) the technique to normalize and aggregate the indicators into sustainability scores. The number of indicators has been reduced to 20 based on experts' comments discussed in Chapter 3. The questionnaire used in this article is in Appendix B. The indicators' info sheets are in Appendix C.

Summary

Point-of-use and point-of-entry drinking water treatment systems are gaining prominence, for certain applications, from the point-of-view of technical appropriateness and consumer acceptance. Research, development, regulatory acceptance, and marketing efforts have made these devices an increasingly viable alternative for small water treatment systems or in individual homes. However, sustainability concerns have been voiced in a number of studies investigating these devices. In this article, sustainability is defined as the fulfillment of treatment systems for a set of technical, economic, environmental, and socio-cultural objectives. Consequently, the use of a hierarchy of sustainability indicators to compare various point-of-use and point-of-entry water treatment alternatives is proposed. The indicators' definitions, as well as calculation and normalization methods are explained. The article also presents a decision model that is capable of selecting the most sustainable treatment option. The model employs the Analytical Hierarchy Process (AHP), a recognized multi-criteria decision analysis tool, to help in the analysis of indicators' relative importance with regard to sustainability and develop the indicators and criteria weights required for aggregating a sustainability score. The generated sustainability scores essentially level the playing field when comparing point-of-use and point-of-entry systems for technical and economic appropriateness for a particular water treatment case, in addition to incorporating more difficult-to-quantify system traits such as environmental and socio-cultural sustainability.

Keywords: Point-of-use and point-of-entry water treatment; sustainability; indicators; multi-criteria decision analysis; analytical hierarchy process

4.1 Introduction

In light of increasing complexity there is a continuous search for feasible and effective solutions for supplying drinking water. Traditional water treatment and supply follows a centralized model, where water in most instances is treated in relative proximity to a source and then distributed through a complex pipe network to the point of use. This centralized model has been successful for decades; however, several recent changes have accelerated the need to find, in certain situations, complementary and alternative solutions to this traditional model (Cotruvo, 2003; Hamouda *et al.*, 2010). These changes include the rise in consumer awareness of drinking water quality issues, the identification of new classes of emerging contaminants, and the need to alleviate the risk from contaminants forming, growing, leaching from pipe and fittings in the distribution system, or those deliberately or accidentally introduced. In addition to these changes, there is the persistent challenge of finding a feasible treatment solution for small, rural, and remote communities, which often suffer from financial constraints that would preclude the construction of full-scale centralized treatment plants (Hamouda *et al.*, 2010).

With these pressing challenges and changes, non-traditional solutions are now at least being considered. Point-of-use (POU) and point-of-entry (POE) water treatment systems represent two of the non-traditional options available (Cotruvo and Cotruvo, 2003; Peter-Varbanets *et al.*, 2009; Raucher *et al.*, 2004). These systems have been around for over 50 years; however, with the establishment of regulatory and certification frameworks for water treatment systems, it has become more challenging for such systems to be accepted for compliance. The water quality association (WQA) which represents the residential, commercial, industrial, and small community water treatment industry in North America initiated efforts to standardize these products to be considered as a potential solution, by issuing the ‘Gold Standard’ in 1960. Since then the growing interest in POU and POE units has led to a rapid increase in the number of units marketed as potential solutions to real or perceived drinking water issues. In 1968 the USEPA responded to the dramatic increase in available devices by assigning NSF International to issue a series of standards to ensure the effectiveness of POU and POE systems (Hamouda *et al.*, 2010). Since then, there has been steady progress in the field of POU and POE treatment in terms of research conducted, standards issued, and finally acceptance for compliance with drinking water regulations—which in the United States occurred in 1996—(USEPA, 2002).

Many studies have investigated target contaminant removal efficiencies of POU and POE systems and their potential to comply with regulations (Abbaszadegan *et al.*, 1997; Deshommes *et al.*, 2010; Pontius *et al.*, 2003; Smith and Komos, 2008; Souter *et al.*, 2003; Sublet *et al.*, 2003; Thomson *et al.*, 2003). However, in selecting among the various POU and POE alternatives, the decision should result in the most sustainable solution, which is not confined to aspects of technical performance. Given the unique nature of point-of-use and point-of-entry water treatment, there are many economic, social, and environmental concerns that fall under the goal of implementing a sustainable water treatment system (Anderson and Sakaji, 2007). 'Sustainable' in this context refers to a hierarchy of parallel criteria that capture the relative fulfillment by various POU and POE treatment systems of the following objectives: (a) provides safe drinking water to help maintain good human health and hygiene; (b) having minimum negative impact on the environment; (c) making better use of human, natural, and financial resources; (d) having a high degree of functional robustness and flexibility; and (e) gains cultural acceptance, thus encouraging responsible behavior by the users. Hamouda *et al.* (2010) suggested a framework that encompasses a number of criteria that assess the sustainability of POU and POE systems to help compare and select the most sustainable solution to a specific treatment case.

To operationalize the selection framework there are several techniques that can be implemented to quantify the various criteria and make an informed decision (Hamouda *et al.*, 2009; Lai *et al.*, 2008). This chapter demonstrates how the sustainability indicators of POU and POE systems were quantified and aggregated into a sustainability score that can be used to compare various treatment alternatives and select among them.

4.2 Background

4.2.1 POU and POE Selection Framework and Stakeholders' Interests

Hamouda *et al.* (2010) described a conceptual framework to select a sustainable POU or POE system, identifying the five stages required for development of the decision support system (Figure 4.1). The first stage involves a systems analysis of the various aspects of implementing a POU or POE system. The findings of the systems analysis can be summarized as follows:

- The most important factor contributing to the rise in the use of POU and POE treatment is the increase in consumer awareness about water issues including aesthetic considerations and their perceptions about the safety of centrally treated water. Other factors include the interest in POU and POE systems: (1) as a means of reducing risk and providing a sense of security; (2) as a drinking water treatment alternative for small, rural, or remote communities especially where groundwater is the source; and (3) as part of a decentralized water treatment strategy where some contaminants can be removed at the small-scale or point-of-use and point-of-entry level.

- Six main stakeholder groups are (or should be) important for overseeing or having involvement with the implementation of such treatment systems. The various interests of these stakeholders are explained in Table 4.1.
- Several drinking water regulations now include acceptance of POU and POE treatment as alternative technologies to comply with maximum contaminant levels. Examples of such regulations include section 1412(b)(4)(E)(ii) of the US Safe Drinking Water Act of 1996, regulation 170/03 of the Ontario (Canada) Safe Drinking Water Act 2006, and section 3.1 of the British Columbia (Canada) Drinking Water Protection Act 2005.

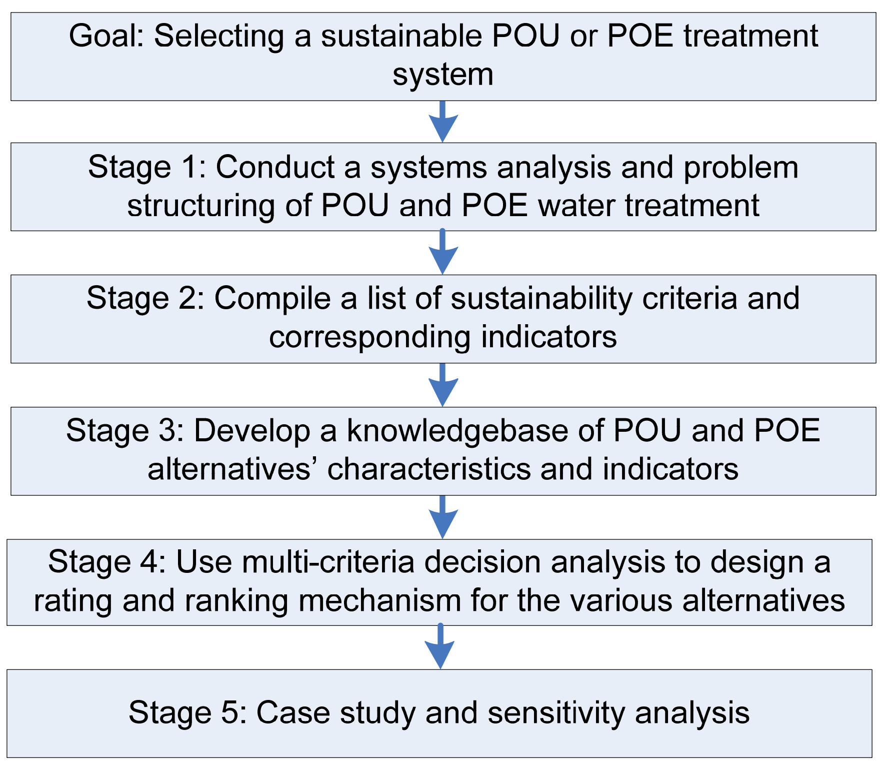

Figure 4.1 A framework for selecting sustainable point-of-use and point-of-entry water treatment systems

Table 4.1 Stakeholders and their interests in point-of-use and point-of-entry water treatment

Stakeholder	Interest in POU and POE water treatment
Government monitoring agency	Installed systems must comply with regulations and performance standards ensuring consumer safety
Water purveyor	Installed systems meet customer satisfaction goals, regulatory requirements and ensure technical and economic sustainability
POU and POE systems supplier/manufacturer associations	Enhance consumer confidence and increase market share to ensure sustained profits
Independent certification organization	More trust in certified versus uncertified products should lead to increased certification requests, and consumer safety
Water associations	Promoting research and consumer awareness regarding the various water treatment alternatives, and the strategies and responsibilities they entail
Consumers and consumer organizations	Make sure concerns about water quality and quantity are met and investigate the feasibility, long-term performance, and after-sale services

- Sustainability issues related to point-of-use and point-of-entry water treatment include: (1) logistical challenges and distribution of responsibilities among stakeholders; (2) stakeholders' involvement in decision-making processes; (3) risk of failure either from improper operation or unit malfunction; (4) cost variability depending on the level of treatment and the quantity of water treated; (5) the lack of information needed to choose among a multiplicity of units, which is exacerbated by the overwhelming market growth of POU and POE systems; and (6) waste management concerns with regard to the disposal of spent cartridges, media, membranes, bulbs, and filters at the end of their useful life.

Stage 2 is also detailed in Hamouda *et al.* (2010) and is briefly summarized in the next section. It involves employing cognitive thinking and expert judgment to develop a hierarchy of criteria to assess the sustainability of various POU and POE alternatives.

4.2.2 Conceptual Development of Sustainability Indicators

Defining criteria and indicators is the basis for constructing the selection mechanism. Sustainability indicators have been used by many researchers and managers in water and wastewater treatment. Most of these indicators evaluate the ability of a treatment system to meet health-related, environmental, economic, social/cultural, and technical objectives (Balkema *et al.*, 2002; Loucks and Gladwell, 1999; Lundin *et al.*, 1999; Mels *et al.*, 1999; Otterpohl *et al.*, 1997).

The conceptual exercise of outlining relevant criteria and indicators is usually subjective and starts by reviewing the available sets of indicators identified in previous studies, then developing an initial list of indicators, followed by the selection of a candidate list of indicators based on empirical analysis, pragmatism or some combination thereof. To alleviate subjectivity, stakeholders' involvement is important when developing the indicators. Hamouda *et al.* (2010) explain the development of a list of 25 indicators that can be used to evaluate the sustainability of POU and POE water treatment systems. Stakeholders were involved through the use of a questionnaire to solicit the opinion of 15 experts, in the field of water treatment in general and POU and POE water treatment in particular, on the developed indicators. The questionnaire successfully stimulated a discussion of the proposed indicators and resulted in improving the indicators to more effectively assess the sustainability of various POU and POE water treatment alternatives. While the conceptual relevancy of the indicators is important, it is also crucial to operationalize the evaluation of these indicators through a practical and preferably quantitative approach (Afgan, 2008; Hamouda *et al.*, 2009). Many of the developed indicators either assess qualitative characteristics, such as device level of decorative attention, or quantitative characteristics, such as energy consumption, for which data may be difficult to find or unavailable.

This chapter describes stages 3 and 4 of the selection framework (Figure 4.1), which deal with operationalizing the selection process by evaluating sustainability criteria and indicators, and applying a multi-criteria decision analysis (MCDA) method to help structure and automate the selection process. Particularly, this chapter sheds light on the various aspects of the calculation of indicators using quasi-quantitative techniques and implementing the analytical hierarchy process as a MCDA method.

4.3 Methods

4.3.1 Calculation of Indicators

Deciding on how the indicators will be calculated and aggregated is perhaps the most critical step in developing a decision support system. Since indicators are the building blocks of the decision process their evaluation should reflect their description. Failure to capture the description of the indicators renders the developed decision support system invalid and the developed indicator weights irrelevant. Moreover, quantitative, quasi-quantitative, and qualitative indicators, like those used in our study, require special attention to design an effective calculation method. The list of 25 indicators developed by Hamouda *et al.* (2010) was revisited and refined using a number of logical filters, these are:

1. Overlapping which leads to exaggeration or over-emphasis of one factor and its contribution to the overall rating of sustainability;
2. Availability of data in the required format; and
3. Existence of sufficient variability among POU and POE systems in the aspect measured by the indicator, such that discrimination among devices in terms of sustainability can be attained.

Clear and detailed definitions of the methods of calculation for all indicators need to be designed to allow for characterizing current and future POU and POE alternatives added to the knowledgebase. Calculation of the indicators took into consideration that the:

1. The indicator calculation method results in a value that represents what the indicator is intended to measure;
2. The method of calculation is clear and not too complicated; and
3. Indicators are normalized for the purpose of aggregation.

In this study it was decided to normalize all the indicators within the range from 0 to 1 where a higher value indicates a contribution to a more sustainable treatment system (i.e. is more desirable). This normalization helped in the aggregation of the indicators. The selection of the normalization method is not trivial and depends on the variables used in evaluating each indicator (Nardo *et al.*, 2005). Different normalization methods were explored, however only two were chosen. These are: (1) Rescaling: normalizing with respect to the range of scores of all the alternatives being compared; it is calculated as the ratio of the difference between the raw variable (or indicator) value and the minimum value, divided by the range; and (2) Categorical scales: a variable (or indicator) is assigned a categorical score, which is qualitative (e.g. 'None', 'Low', 'Moderate', 'High', and 'Very high') with a corresponding numerical value (e.g. 0, 0.25, 0.5, 0.75, and 1).

Normalization should consider the data properties and the objectives of the aggregated score. Nardo *et al.* (2005) outlined the issues that could guide the selection of the normalization method: whether quantitative or qualitative data are available, whether exceptional values need to be rewarded/penalized, and whether the variance in the indicators needs to be accounted for. For example, in this study, when the indicator values were within a small interval and small changes in the indicator's value could have a significant effect of the sustainability score, the rescaling method was used. On the other hand, when the indicator was assessing soft qualitative aspects or when small changes in such aspects should not affect the aggregated sustainability score, the categorical scale method was used.

4.3.2 Application of Multi-Criteria Decision Analysis

Numerous multi-criteria decision analysis techniques have been employed in decision support systems developed to design or select among water and wastewater treatment systems. These are reviewed elsewhere (Hamouda *et al.*, 2009; Lai *et al.*, 2008). The analytical hierarchy process (AHP) and its generalized form, the Analytic Network Process (ANP), are two multi-criteria decision analysis methods that were developed by Saaty (2008). AHP/ANP can be employed by following a conceptually sound and practical approach for defining, weighting, and aggregating individual indicators to evaluate sustainability. The AHP/ANP rationality is based on breaking down the decision model into smaller constituents and then doing pairwise comparisons to indicate the relative influence of various factors on the outcome (Saaty, 2008). The main difference between AHP and ANP is that while ANP structures the problem as clusters of elements connected in a network, AHP involves organizing the elements in a hierarchical format. ANP may offer a model that is closer to reality where structuring the decision problem in hierarchical form is unrealistic. Although AHP/ANP was designed for subjective evaluation, this can be compensated for by ensuring stakeholders' involvement.

AHP was selected in this case because it is sufficiently logical to structure the problem and decision model in a hierarchical form that contains the various indicators and criteria influencing the decision. It is also reasonably assumed that stakeholders will be able to make pairwise comparisons to indicate the difference in the degree of importance of each of two indicators on the outcome (Saaty, 2008), which in our case is the sustainability rating of point-of-use and point-of-entry water treatment systems. Moreover, the hierarchical structure of the AHP process allows for utilizing aggregation of sub-categories of factors influencing the decision, which enable blocking factors that may be thought of as irrelevant by different users. This adds to the flexibility and utility of a decision support system and enables user interactiveness.

The following sections explain how AHP was implemented to evaluate POU and POE systems' sustainability. Figure 4.2 summarizes the entire process of implementing the AHP technique, including the weighting and aggregation of indicators to calculate a sustainability score.

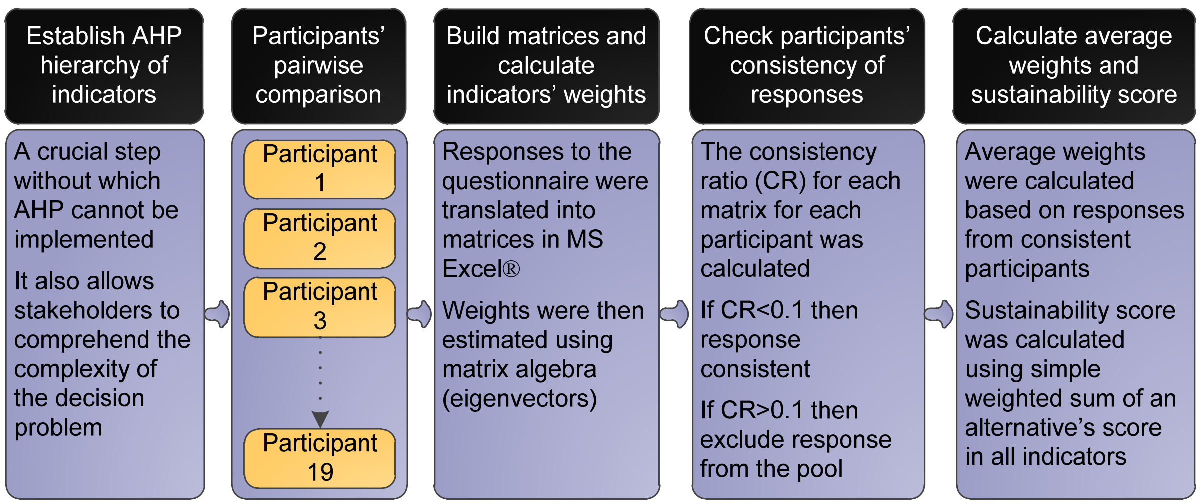

Figure 4.2 Summary of AHP implementation method

4.3.2.1 Establishment of a structural hierarchy

This step allows a complex decision to be structured into a hierarchy descending from an overall goal to various 'criteria', 'sub-criteria', and so on until the lowest level. According to Saaty (2008), a hierarchy can be constructed by creative thinking, recollection and using stakeholders' perspectives. The hierarchy of indicators which were identified and used to compare and select among POU and POE alternatives is depicted in Figure 4.3.

The AHP hierarchy outlined in Figure 4.3 consists of various levels, these are:

1. An overall goal of maximizing the sustainability of a point-of-use and point-of-entry water treatment alternative;

2. A group of criteria (technical, economic, environmental, and sociocultural) that outline the various aspects of sustainability;

3. A number of underlying objectives to maximize performance, implementability, operability, consumer acceptance, and product availability, while minimizing life cycle cost, environmental footprint, and resource consumption;

4. A list of indicators (20) that relate the treatment system alternatives to the overall sustainability goal;

5. A variety of POU and POE treatment system alternatives from which the most sustainable will be selected.

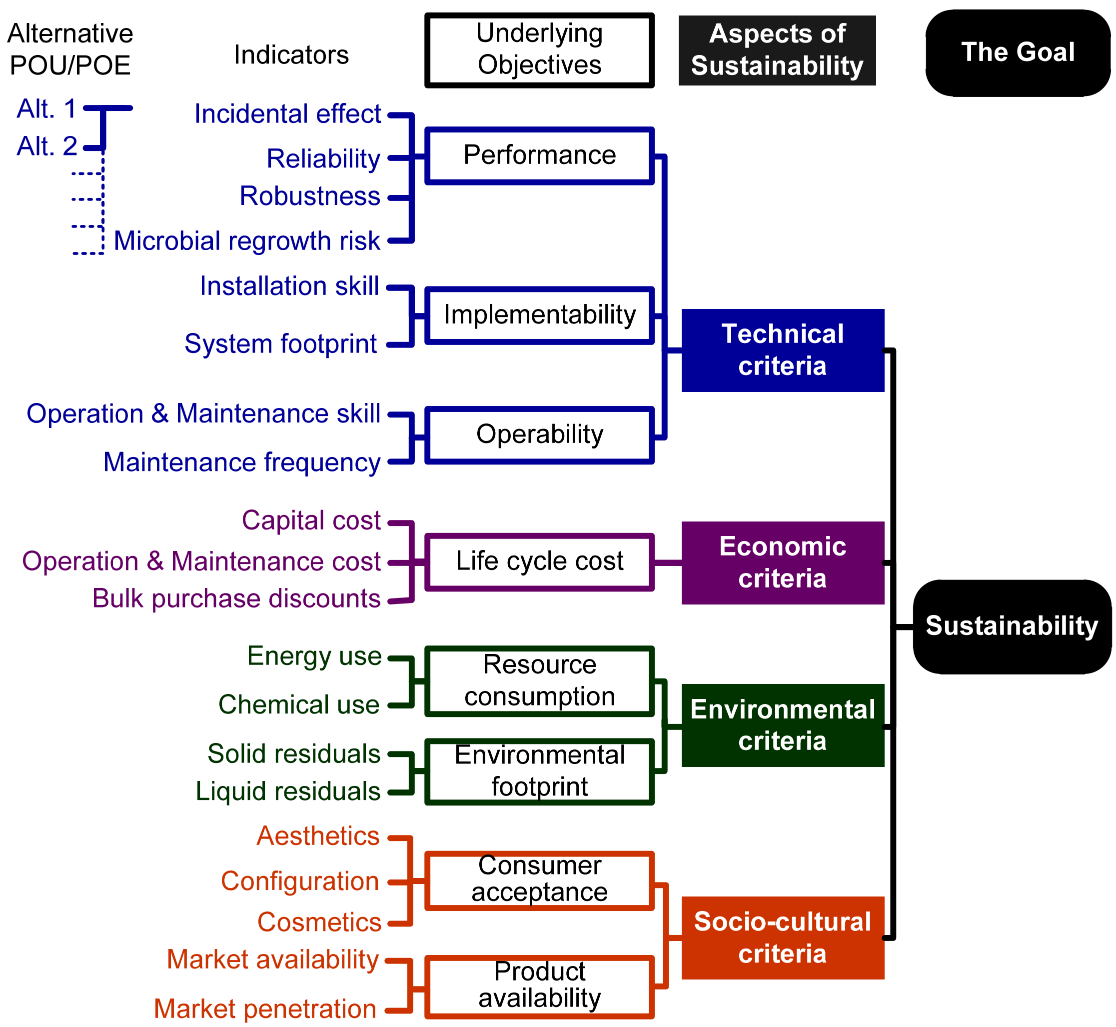

Figure 4.3 The AHP hierarchy used to evaluate the sustainability of a POU/POE device

4.3.2.2 Judgment through pairwise comparison

To employ a number of indicators to evaluate the sustainability of a large number of point-of-use and point-of-entry water treatment systems, it is essential to establish the relative importance of each indicator based on performance requirements and stakeholders' needs. It may also be beneficial to use aggregation techniques to calculate an overall score with respect to all the indicators to outline the preferred alternatives that may be selected (Lai *et al.*, 2008, Saaty, 2008). Once the hierarchy has been established, a matrix can be constructed within which elements in each level of the hierarchy—indicator, objective, and criteria group—and between levels are compared pairwise. The result is a clear priority statement of a participant. This technique is employed by decision support systems developers, sometimes even by those who are not using AHP (Simon *et al.*, 2004).

A questionnaire was designed to explain the objectives of the study and request stakeholders' judgment on which of two criteria groups, objectives, or indicators is more important in fulfilling the overall sustainability goal or any of its underlying objectives (pairwise comparison). The participants were asked to tick a box that represented the relative importance between two indicators based on Saaty's scale (Figure 4.4). In Saaty's scale, a judgment that two indicators are equally important is given 1, moderately more important 3, strongly more important 5, very strongly more important 7 and extremely more important 9. The pairwise comparisons result in a (NxN) positive reciprocal matrix, where the diagonal $a_{ii} = 1$ and reciprocal property $a_{ji} = (1/a_{ij})$, assuming: if a participant's judgment "X" is that indicator i is ''X-times'' more important than indicator j, then, necessarily, indicator j is ''1/X-times'' the importance of indicator i.

Nineteen participants representing various stakeholders in point-of-use and point-of-entry water treatment—outlined earlier in Table 4.1—responded to the questionnaire and their responses were recorded in a Microsoft® Excel® spreadsheet. The responses were used to build a decision matrix for each objective and each criteria group, and for sustainability (Tables 4.2, 4.3, and 4.4 respectively). The relative importance values for Table 4.2 come from Figure 4.4. In Table 4.2, initially, the diagonal is given values of 1, then the first row of the matrix is built, i.e., the relative importance of the Incidental Effect indicator with respect to indicators of Reliability, Robustness, and Microbial regrowth risk (inversely strongly more important = 1/5). Then the process of comparison is repeated for each row of the matrix after the diagonal cell using the participant's judgment. The remaining cells below the diagonal are filled using reciprocal judgments ($a_{ji} = 1/a_{ij}$) over each pair of indicators. At the end of the comparisons, the matrix is filled with the relative importance values. Similar matrices were developed for a participant's pairwise comparison of other indicators to give the relative importance of all the elements in the hierarchy outlined earlier in Figure 4.3.

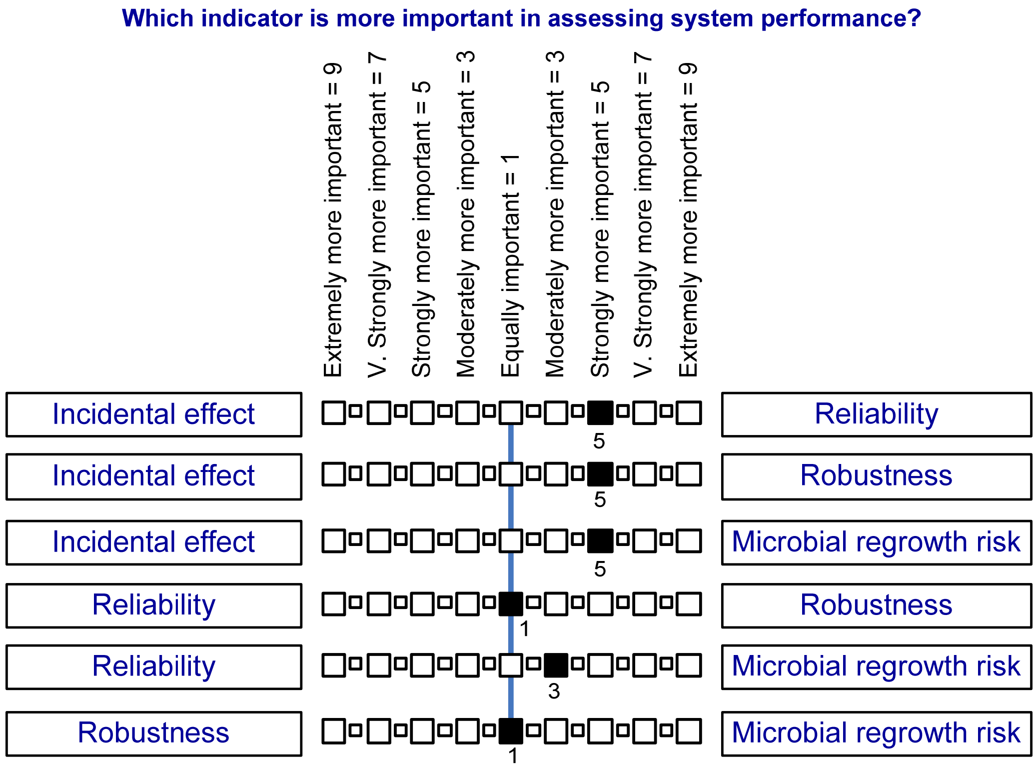

Figure 4.4 Excerpt from an actual participant's response to the pairwise comparison questionnaire

Table 4.2 A participant's pairwise comparison matrix for the objective of maximizing performance

Performance	Incidental effect	Reliability	Robustness	Microbial regrowth risk
Incidental effect	1.00	0.20	0.20	0.20
Reliability	5.00	1.00	1.00	0.33
Robustness	5.00	1.00	1.00	1.00
Microbial regrowth risk	5.00	3.00	1.00	1.00

Table 4.3 A participant's pairwise comparison matrix for the technical criteria group

Technical	Performance	Implementability	Operability
Performance	1.00	5.00	4.00
Implementability	0.20	1.00	1.00
Operability	0.25	1.00	1.00

Table 4.4 A participant's pairwise comparison matrix for sustainability criteria groups

Sustainability	Technical	Economic	Environmental	Socio-cultural
Technical	1.00	3.00	1.00	3.00
Economic	0.33	1.00	0.33	1.00
Environmental	1.00	3.00	1.00	3.00
Socio-cultural	0.33	1.00	0.33	1.00

The built matrices (Tables 4.2, 4.3, and 4.4) represent the input of one participant. These were used to calculate the relative weights of indicators, objectives, and criteria groups, based on that participant's judgment.

4.3.2.3 Determining weights

The next step is the analysis of the pairwise comparison matrix to obtain the relative weights of the indicators, objectives, and criteria groups. Saaty (2003) has shown that solving the principal eigenvector of the matrix will provide an excellent estimate of the relative weights of the indicators indicating their priority level. The principal eigenvector is calculated using a simple iterative method designed in MS Excel®. The method used calculates in each iteration an even power (squaring) of the matrix A^{2x} ($x = 1, 2, \ldots, m$). The resulting matrix is then used to estimate the eigenvector by summing the rows and then normalizing the resulting vector (Ishizaka and Lusti, 2006). In each iteration the difference between the eigenvector estimates was calculated to ensure convergence of the solution. The iteration was stopped when differences were not detected to the third decimal place with a minimum of three iterations. Table 4.5 shows the eigenvector calculated for the pairwise comparison matrix for the objective of maximizing performance (outlined in Table 4.2). The third iteration eigenvector is an estimate of the principal eigenvector which is the relative weights vector.

Table 4.5 Calculating the eigenvector for indicators influencing system performance

Indicators Influencing Performance	IE	RL	RB	MR	Eigenvector Iteration 1	Eigenvector Iteration 2	Eigenvector Iteration 3
Incidental effect (IE)	1.00	0.20	0.20	0.20	0.0558	0.0598	0.0596
Reliability (RL)	5.00	1.00	1.00	0.33	0.3863	0.3823	0.3825
Robustness (RB)	5.00	1.00	1.00	1.00	0.3863	0.3823	0.3825
Microbial regrowth risk (MR)	5.00	3.00	1.00	1.00	0.1717	0.1756	0.1753

4.3.2.4 Checking for consistency

As mentioned earlier, the pairwise comparison matrix is a positive reciprocal matrix with values (a_{ij}) that represent the weights ratios (relative importance w_i/w_j) of the indicators. A matrix of pairwise comparison can thus be given as follows:

$$A = \begin{bmatrix} a_{11} & a_{12} & . & . & . & a_{1n} \\ a_{21} & a_{22} & . & . & . & a_{2n} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ a_{n1} & a_{n2} & . & . & . & a_{nn} \end{bmatrix} = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & . & . & . & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & . & . & . & \frac{w_2}{w_n} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & . & . & . & \frac{w_n}{w_n} \end{bmatrix} \tag{1}$$

Furthermore, if a participant's judgment is presumed consistent, another property of the matrix is that:

$$a_{ij} = \frac{w_i}{w_j}, a_{ik} = \frac{w_i}{w_k}, a_{jk} = \frac{w_j}{w_k}, \therefore a_{ij} = \frac{a_{ik}}{a_{jk}} \tag{2}$$

This means that if Reliability is strongly more important that Incidental effect (i.e. a_{ik} =5) and at the same time Robustness is strongly more important than Incidental effect (i.e. a_{jk} =5), then the ratio (relative importance) of Robustness with respect to Reliability $a_{ij} = a_{ik}/a_{jk}=5/5 =1$, i.e. they are equally important. Looking at Figure 4.4 and Table 4.2, the consistency assumption holds in this case, however, consistency cannot be assumed for all judgments. In fact, inconsistencies often exist in pairwise comparison matrices and therefore such small perturbations in the coefficients imply small perturbations in the eigenvalues. A consistency ratio (CR) was calculated for each pairwise comparison matrix to check the consistency of each participant's judgment. Careless or exaggerated judgments during the process of pairwise comparison may result in such inconsistencies. To calculate the consistency ratio we first calculated the consistence index (CI) of n criteria:

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{3}$$

Where λ_{max} is the largest eigenvalue of a pairwise matrix A, which can be calculated using the following relation:

$$A.\underline{w} = \lambda_{\max}.\underline{w} \qquad (4)$$

Where $\underline{w}$ is the weights vector (principal eigenvector) corresponding to A. Since we already obtained A and $\underline{w}$, λ_{max} can be easily obtained by solving (4). For example, using the same matrix shown in Tables 4.2 and 4.5 the largest eigenvalue λ_{max} was calculated as follows:

$$\lambda_{\max} = \frac{[(1\times 0.0596)+(0.2\times 0.3825)+(0.2\times 0.3825)+(0.2\times 0.1753)]}{0.0596} = 4.155 \qquad (5)$$

Then the consistency ratio (CR) was calculated as follows:

$$CR = \frac{CI}{RI} = \frac{\lambda_{\max} - n}{n-1} \times \frac{1}{RI} = \frac{4.155-4}{4-1} \times \frac{1}{0.9} = 0.0574 \qquad (6)$$

Where RI is the Random Index which depends on matrix size n:

n:	**3**	**4**	**5**
RI:	**0.58**	**0.9**	**1.12**

The ratio can range from 0.0, which reflects perfect consistency to 1.0, which indicates no consistency. 0.1 is recommended as the maximum acceptable value for the CR (Saaty, 2003). Participant's judgments with CR ratios higher than 0.1 were disregarded in calculating the average weights. The example given in (6) is then considered of acceptable consistency since CR = 0.06 (< 0.1).

4.3.2.5 Aggregating a sustainability score

Participants' responses were considered of equal importance. Thus, the averages of indicators' weights resulting from all consistent participants' responses to the questionnaire were used to calculate the aggregated score evaluating a point-of-use and point-of-entry water treatment system's sustainability. For a number of participants (m) with CR < 0.1 the average weight is:

$$Average \;\; Weight = \sum_{a=1}^{m} \frac{w_a}{m} \qquad (7)$$

Where w_a is the weight of an indicator resulting from participant a's response.

To obtain an overall rating of sustainability we multiplied the normalized criteria and indicators' scores of alternative point-of-use and point-of-entry water treatment systems by the corresponding eigenvector weights of the criteria and sum. Since the indicators were normalized such that their values ranged from 0-1; they would thus contribute negatively to sustainability if their values are closer to 0, whereas a value closer to 1 would mean a positive contribution to sustainability (i.e. the alternative being evaluated is more sustainable in the aspect being evaluated by the indicator). Aggregation was done using a simple linear function based on an alternative's score on the various indicators (a_i) and the indicators' weights (w_i). Thus to evaluate and aggregated value of sustainability of a point-of-use and point-of-entry water treatment system, the following equation was used:

$$Sustainability \quad Score = \sum_{k=1}^{4} w_k \left[\sum_{j=1}^{m} w_j \left(\sum_{i=1}^{n} a_i w_i \right)_j \right]_k \tag{8}$$

Where:

a_i = normalized alternative's score for the various indicators under objective j

n = number of indicators under objective j

w_i = indicators' weights denoting their relative importance with respect to achieving objective j

w_j = objectives' weights denoting their relative importance under the technical, economic, environmental, or socio-cultural criteria group

m = number of objectives under criteria group k

w_k = weights of criteria categories denoting their importance with respect to achieving sustainability

Similar weighted sum equations were used to get the scores of an alternative for a particular criteria group (technical, economic, environmental, or sociocultural) and for a particular objective (performance, implementability, etc.).

4.4 Results

4.4.1 Indicators and Their Calculation

After applying the logical filters for the 25 indicators developed by Hamouda *et al.* (2010), the final list of indicators was narrowed down to 20. The 5 indicators removed from the list either had overlapping effect (e.g. indicator of system complexity), insufficient data availability, or insufficient variability among alternatives (e.g. indicator of removal efficiency). Indicator information sheets, such as the example shown in Table 4.6, are one of the most significant outcomes of the decision analysis exercise. Information sheets for each of the 20 indicators were developed.

Table 4.6 Reliability indicator information sheet

<table>
<tr><td>Criteria Group</td><td>Technical</td><td>Objective</td><td>Maximize Performance</td></tr>
<tr><td>Indicator of</td><td colspan="3">Reliability</td></tr>
<tr><td>Description</td><td colspan="3">A quantitative assessment of the sensitivity to malfunctioning by measuring redundancy in the treatment train.</td></tr>
<tr><td>Evaluation</td><td colspan="3">The equation used to evaluate reliability
$RL = \frac{P - P_{\min}}{P_{\max} - P_{\min}}$
P : redundant processes in a device used to remove a target contaminant (= number of processes removing that contaminant – 1)
P_{max}: Highest number of redundant processes in a device used to remove a target contaminant
P_{max}: Lowest number of redundant processes in a device used to remove a target contaminant
The indicator is evaluated for a number of important contaminants, these are: lead, arsenic, chromium (hexavalent), cysts, fluoride, MTBE, nitrite/nitrate, radon, perchlorate, and VOC contaminant category.
There are three cases for the indicator’s calculation:
1. If there are no target contaminants identified in the case or if the target contaminant is not one of the main contaminants, then all the devices are rated equally for reliability and are given a value of 1.
2. If there is only one target contaminant identified and belongs to the group of main contaminants, then the reliability of a device is that calculated for this one target contaminant.
3. If there is more than one target contaminant identified belonging to the group of main contaminants, then the reliability of a device is the lowest reliability of those calculated for each target contaminant.</td></tr>
</table>

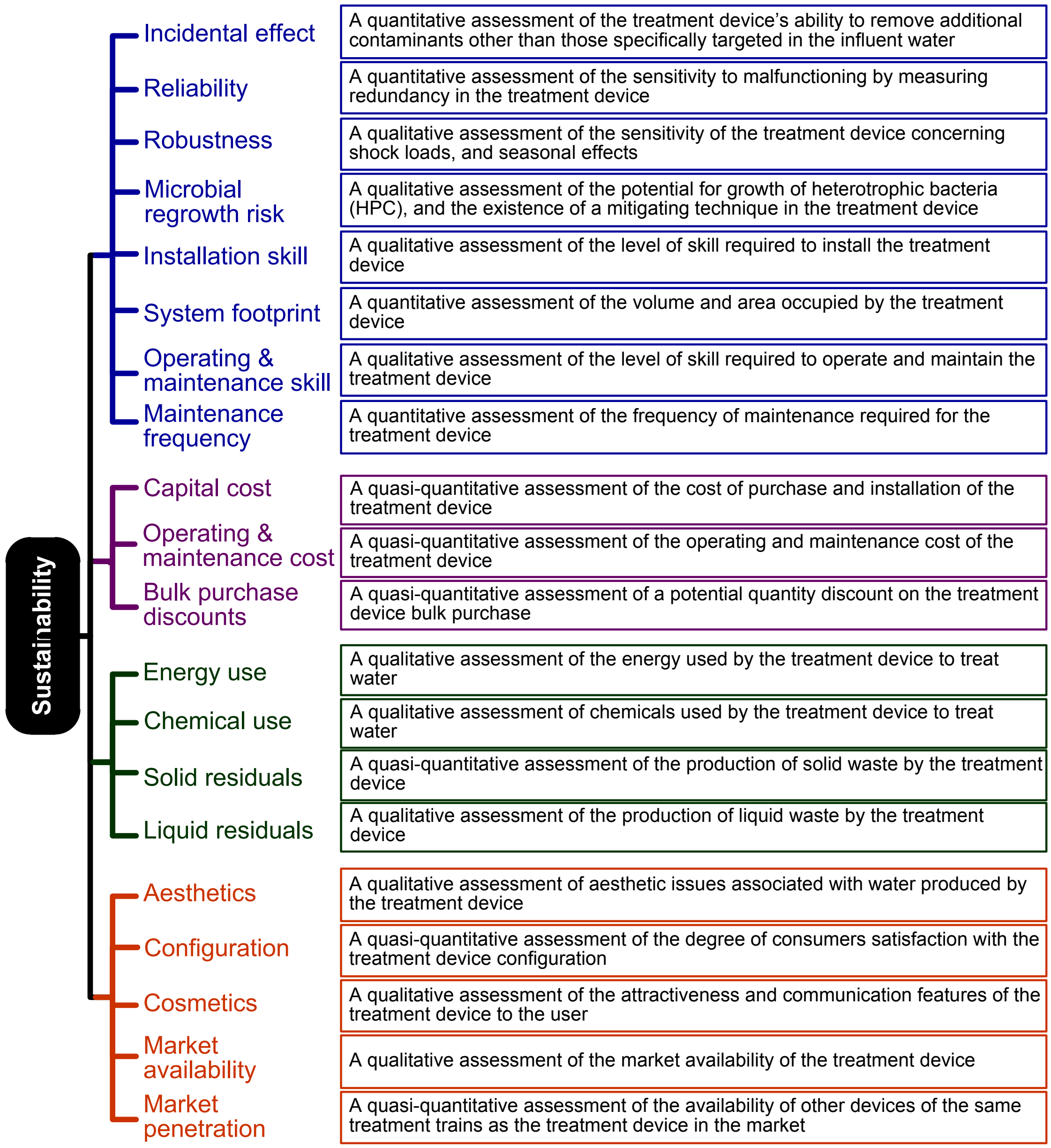

Figure 4.5 Refined list of sustainability indicators and their definitions

Figure 4.5 illustrates the list of indicators, their type (qualitative, quantitative, or quasi-quantitative), and their definitions. Table 4.7 shows a summary of the indicators characteristics, including: (1) parameters used in calculation; (2) type of normalization used: rescaling or categorical scales ('None', 'Low', 'Moderate', 'High', and 'Very high' with a corresponding numerical value of zero, 0.25, 0.5, 0.75, and 1); and (3) type of aggregation of parameters to calculate the indicator's value: mutual equivalence, weighted sum, or complex categorical scales.

Table 4.7 Indicators' parameters, normalization methods, aggregation methods, and calculation formulae

Indicator	Parameters	Normalization	Aggregation	Calculation Formula
IE: Incidental effect	1. CR : number of contaminants removed by the treatment device (certified to NSF/ANSI stds.)	1. Rescaling	N/A	$IE = \frac{CR - CR_{\min}}{CR_{\max} - CR_{\min}}$
RB: Robustness	1. SR: Risk of shock loads emanating from source water type 2. WR: The level of sophistication of the device's warning mechanism in terms of: i. PC: Product control method ii. FA: Failure alarm type	1. Categorical scale 2. i. Categorical scale ii. Categorical scale	Mutual equivalence	$WR = PC + FA - PC \times FA$ $RB = SR + WR - SR \times WR$
MR: Microbial regrowth risk	1. RR: Regrowth risk which depends on the processes in the treatment device 2. MT: Indicating whether a mitigation technique follows treatment units facilitating biofilm growth	1. Categorical scale 2. Categorical scale	Complex categorical	N/A
IS: Installation skill	1. IS: ease of installing the treatment device	1. Categorical scale	N/A	N/A
SF: System footprint	1. A: Area occupied by the treatment device 2. V: Volume occupied by the treatment device	1. Rescaling 2. Rescaling	Weighted sum	$SF = \frac{1}{2}\frac{V_{\max} - V}{V_{\max} - V_{\min}} + \frac{1}{2}\frac{A_{\max} - A}{A_{\max} - A_{\min}}$
OS: Operating and maintenance skill	1. DC: Difficulty for changing the device's components 2. CL: Sophistication of the cleaning operations	1. Categorical scale 2. Categorical scale	Weighted sum	$OS = \frac{1}{2}DC + \frac{1}{2}CL$
MF: Maintenance frequency	1. SL: Service life until maintenance in liters of treated water 2. CO: Number of components to be changed	1. Rescaling 2. Rescaling	Weighted sum	$MF = \frac{3}{4}\frac{SL - SL_{\min}}{SL_{\max} - SL_{\min}} + \frac{1}{4}\frac{CO_{\max} - CO}{CO_{\max} - CO_{\min}}$
CC: Capital cost	1. PC: Purchase cost estimated (CAD) 2. IC: Installation cost which is estimated based on the installation skill indicator	1. Rescaling 2. Categorical scale	Weighted sum	$CC = \frac{2}{3}\frac{PC_{\max} - PC}{PC_{\max} - PC_{\min}} + \frac{1}{3}IC$
OC: Operating and maintenance cost	1. RC: Replacement components' cost divided by the service life of the device 2. EC: Electricity cost rating 3. SC: Service cost rating	1. Rescaling 2. Categorical scale 3. Categorical scale	Weighted sum	$OC = \frac{2}{5}\frac{RC_{\max} - RC}{RC_{\max} - RC_{\min}} + \frac{1}{5}EC + \frac{2}{5}SC$

Indicator	Parameters	Normalization	Aggregation	Calculation Formula
BPD: Bulk purchase discounts	1. DP: Discount percentages based on intervals of order value (CAD) 2. OV: Order value (CAD)	1. Categorical scale 2. N/A	N/A	N/A
EU: Energy use	1. EU: Quantity of energy use by the device	1. Categorical scale	N/A	N/A
CU: Chemical use	1. CU: Quantity of chemicals used by the device	1. Categorical scale	N/A	N/A
SR: Solid residuals	1. TC: Whether or not there is a target contaminant to be removed from the source water 2. HS: The presence of any hazardous substance in the non water contacting device materials 3. SQ: Quantity of solid residuals produced by device replacement components	1. Categorical scale 2. Categorical scale 3. Rescaling then categorical scaling	Complex categorical	N/A
LR: Liquid residuals	1. TC: Whether or not there is a target contaminant to be removed from the source water 2. SS: Type of system receiving the liquid waste (domestic sewer, tile, or septic tank) 3. LQ: Quantity of liquid residuals produced	1. Categorical scale 2. Categorical scale 3. Categorical scaling	Complex categorical	N/A
AS: Aesthetics	1. SV: Aesthetic issues rating in terms of severity 2. FR: Aesthetic issues rating in terms of frequency	1. Categorical scale 2. Categorical scale	Complex categorical	N/A
CN: Configuration	1. NC : number of certified treatment devices of a configuration type	1. Rescaling	N/A	$CN = \frac{NC - NC_{\min}}{NC_{\max} - NC_{\min}}$
CM: Cosmetics	1. SH: Device decorative shape and color varieties 2. DP: Display of device performance	1. Categorical scale 2. Categorical scale	Weighted sum	$CM = \frac{1}{2}SH + \frac{1}{2}DP$
MA: Market availability	1. CS: Coverage of chain stores where the device is sold 2. OP: Availability and effectiveness of online and phone ordering	1. Categorical scale 2. Categorical scale	Weighted sum	$MA = \frac{1}{2}CS + \frac{1}{2}OP$
MP: Market penetration	1. TC : number of certified treatment systems that fit a particular treatment train	1. Rescaling	N/A	$MP = \frac{TC - TC_{\min}}{TC_{\max} - TC_{\min}}$

4.4.2 Results of AHP Pairwise Comparison

Table 4.8 shows several outcomes of the indicators' pairwise comparison questionnaire. It illustrates the resulting indicators' weights and their averages which are calculated as explained in section 4.3.2.3. It also shows the consistency ratio (CR) for each pairwise comparison matrix—where applicable (i.e. n>2)—for all participants. Participants that had consistency ratios below the rule-of-thumb value of CR (0.1), were considered in calculating the average weights because they were consistent in assigning pairwise comparison judgments. As shown in Table 4.8, not all the responses of the 19 participants were used in calculating the overall average weights due to inconsistencies in the responses of a few participants.

4.4.3 Sample Outcome of Developed AHP Model

Figure 4.6 is an example of a simple display of the sustainability assessment results of four shortlisted POU treatment alternatives used to remove lead from drinking water. The alternatives are ranked in a descending order from the one with highest sustainability score (alternative 1), and consequently the best solution in this case, to the one with the lowest sustainability score (alternative 4). It is interesting to see that had environmental criteria been the only aspect for consideration in this selection problem, alternative 4 would have had the highest rating.

The utility of the resulting sustainability assessment can be enhanced through visualization of sub-indices. This is easily done through the presentation technique of a radar diagram. A radar diagram displays an alternative's scores on various sustainability criteria groups or objectives in a radial system of axes. If an objective has 'n' underlying assessment indicators, a regular n-sided polygon is formed. Each radius ending at a corner of the polygon is a measuring axis for each indicator. The point where the axes meet corresponds to a value of 0—the lowest score in terms of sustainability. The value corresponding to the corners of the polygon is normalized with a value of 1—the highest score in terms of sustainability. The normalized scores of different indicators and sub-indices of the POU alternative for a particular case are plotted on the corresponding axes. The joining of point scores on all the axes forms a new polygon. Figure 4.7 displays an example of a radar diagram developed for the same four alternatives considered in the lead removal hypothetical case. The figure shows the score of the four alternatives based on the three technical sustainability objectives ignoring the objectives' relative weights. It is clear that even though alternative 1 had the highest sustainability score, it lacks in fulfilling the objective of maximizing implementability, more so than other alternatives. This insight into the fulfillment of underlying objectives can help decision makers and POU and POE device manufacturers identify the reasons for having a lower sustainability rating.

Table 4.8 Questionnaire results; weights, and consistency ratios, for 19 participants

	Participant number																			
Criteria Group, Objective, or Indicator	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**Average Weight**
Technical																				
$W_{Performance}$	0.70	0.47	0.75	0.11	0.33	0.06	0.20	0.73	0.71	0.49	0.65	0.52	0.14	0.46	0.69	0.22	0.33	0.76	0.67	0.42
$W_{Implementability}$	0.10	0.10	0.07	0.11	0.33	0.18	0.10	0.08	0.07	0.08	0.13	0.18	0.28	0.22	0.15	0.65	0.33	0.05	0.07	0.17
$W_{Operability}$	0.20	0.43	0.18	0.78	0.33	0.75	0.70	0.20	0.22	0.44	0.22	0.30	0.58	0.32	0.16	0.13	0.33	0.19	0.26	0.41
CR	0.10	0.00	0.03	0.00	0.00	0.25	0.12	0.38	0.16	0.01	0.25	0.25	0.10	0.10	0.00	0.16	0.00	0.28	0.19	
Economic																				
$W_{Life\ cycle\ cost}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Environmental																				
$W_{Resource\ consum.}$	0.75	0.83	0.75	0.50	0.75	0.88	0.20	0.50	0.88	0.83	0.88	0.75	0.83	0.75	0.75	0.83	0.83	0.13	0.50	0.69
$W_{Env.\ footprint}$	0.25	0.17	0.25	0.50	0.25	0.13	0.80	0.50	0.13	0.17	0.13	0.25	0.17	0.25	0.25	0.17	0.17	0.88	0.50	0.31
Sociocultural																				
$W_{Consumer\ accept.}$	0.83	0.75	0.17	0.50	0.83	0.83	0.88	0.83	0.75	0.75	0.83	0.25	0.83	0.50	0.75	0.83	0.50	0.13	0.83	0.65
$W_{Product\ availability}$	0.17	0.25	0.83	0.50	0.17	0.17	0.13	0.17	0.25	0.25	0.17	0.75	0.17	0.50	0.25	0.17	0.50	0.88	0.17	0.35
Technical-Performance																				
$W_{Incidental\ effect}$	0.06	0.12	0.03	0.06	0.11	0.05	0.12	0.03	0.16	0.06	0.05	0.07	0.07	0.06	0.06	0.13	0.07	0.17	0.05	0.08
$W_{Reliability}$	0.37	0.35	0.15	0.59	0.29	0.42	0.11	0.65	0.36	0.30	0.43	0.60	0.60	0.38	0.23	0.56	0.65	0.15	0.32	0.38
$W_{Robustness}$	0.40	0.29	0.10	0.29	0.57	0.42	0.59	0.11	0.40	0.25	0.43	0.12	0.25	0.38	0.30	0.24	0.23	0.51	0.16	0.36
$W_{Microbial\ regrowth}$	0.17	0.23	0.71	0.06	0.03	0.11	0.18	0.21	0.08	0.39	0.10	0.21	0.07	0.18	0.41	0.06	0.05	0.18	0.47	0.18
CR	0.09	0.10	0.24	0.03	0.16	0.19	0.02	0.22	0.04	0.18	0.07	0.10	0.13	0.06	0.06	0.14	0.19	1.91	0.19	
Technical-Implementability																				
$W_{Insltallation\ skill}$	0.86	0.17	0.88	0.83	0.75	0.25	0.20	0.50	0.83	0.75	0.25	0.75	0.75	0.50	0.25	0.83	0.88	0.83	0.75	0.61
$W_{System\ footprint}$	0.14	0.83	0.13	0.17	0.25	0.75	0.80	0.50	0.17	0.25	0.75	0.25	0.25	0.50	0.75	0.17	0.13	0.17	0.25	0.39
Technical-Operability																				
$W_{O\ \&\ M\ skill}$	0.88	0.83	0.83	0.83	0.25	0.83	0.80	0.50	0.33	0.83	0.20	0.50	0.50	0.50	0.50	0.17	0.50	0.13	0.80	0.55
$W_{Maintenance\ frq.}$	0.13	0.17	0.17	0.17	0.75	0.17	0.20	0.50	0.67	0.17	0.80	0.50	0.50	0.50	0.50	0.83	0.50	0.88	0.20	0.45
Economic-Life Cycle Cost																				
$W_{Capital\ cost}$	0.20	0.30	0.10	0.43	0.46	0.69	0.31	0.47	0.71	0.20	0.79	0.58	0.45	0.62	0.28	0.69	0.75	0.17	0.50	0.37
$W_{O\&M\ cost}$	0.70	0.62	0.64	0.43	0.22	0.23	0.64	0.47	0.24	0.70	0.05	0.28	0.45	0.30	0.58	0.23	0.21	0.74	0.36	0.50
$W_{Bulk\ discount}$	0.10	0.09	0.26	0.14	0.32	0.08	0.05	0.05	0.05	0.10	0.16	0.14	0.09	0.09	0.14	0.08	0.04	0.09	0.14	0.13
CR	0.10	0.10	0.03	0.00	0.10	0.25	0.10	0.00	0.25	0.10	0.22	0.10	0.00	0.10	0.10	0.25	0.38	0.20	1.58	
Environmental-Resource Consumption																				
$W_{Energy\ use}$	0.17	0.17	0.83	0.25	0.17	0.83	0.50	0.50	0.25	0.17	0.83	0.75	0.83	0.75	0.50	0.88	0.50	0.13	0.17	0.50
$W_{Chemical\ use}$	0.83	0.83	0.17	0.75	0.83	0.17	0.50	0.50	0.75	0.83	0.17	0.25	0.17	0.25	0.50	0.13	0.50	0.88	0.83	0.50
Environmental-Environmental Footprint																				
$W_{Solid\ residuals}$	0.50	0.75	0.17	0.50	0.75	0.13	0.17	0.50	0.83	0.17	0.50	0.75	0.88	0.50	0.50	0.17	0.88	0.88	0.50	0.53
$W_{Liquid\ residuals}$	0.50	0.25	0.83	0.50	0.25	0.88	0.83	0.50	0.17	0.83	0.50	0.25	0.13	0.50	0.50	0.83	0.13	0.13	0.50	0.47
Sociocultural-Consumer Acceptance																				
$W_{Aesthetics}$	0.57	0.71	0.69	0.33	0.20	0.75	0.71	0.49	0.65	0.73	0.71	0.32	0.30	0.66	0.44	0.69	0.32	0.33	0.73	0.46
$W_{Configuration}$	0.32	0.14	0.26	0.33	0.60	0.06	0.14	0.44	0.22	0.08	0.22	0.46	0.62	0.16	0.17	0.23	0.46	0.33	0.08	0.33
$W_{Cosmetics}$	0.11	0.14	0.05	0.33	0.20	0.18	0.14	0.08	0.13	0.19	0.07	0.22	0.09	0.19	0.39	0.08	0.22	0.33	0.20	0.21
CR	0.25	0.00	0.34	0.00	0.00	0.25	0.00	0.01	0.25	0.06	0.16	0.10	0.10	0.03	0.02	0.25	0.10	0.00	0.38	
Sociocultural-Product Availability																				
$W_{Market\ availability}$	0.83	0.83	0.13	0.50	0.75	0.17	0.33	0.50	0.75	0.88	0.17	0.50	0.88	0.50	0.50	0.88	0.88	0.13	0.50	0.54
$W_{Market\ penetration}$	0.17	0.17	0.88	0.50	0.25	0.83	0.67	0.50	0.25	0.13	0.83	0.50	0.13	0.50	0.50	0.13	0.13	0.88	0.50	0.46

Shaded areas represent inconsistent responses that were not taken in calculating the average weight

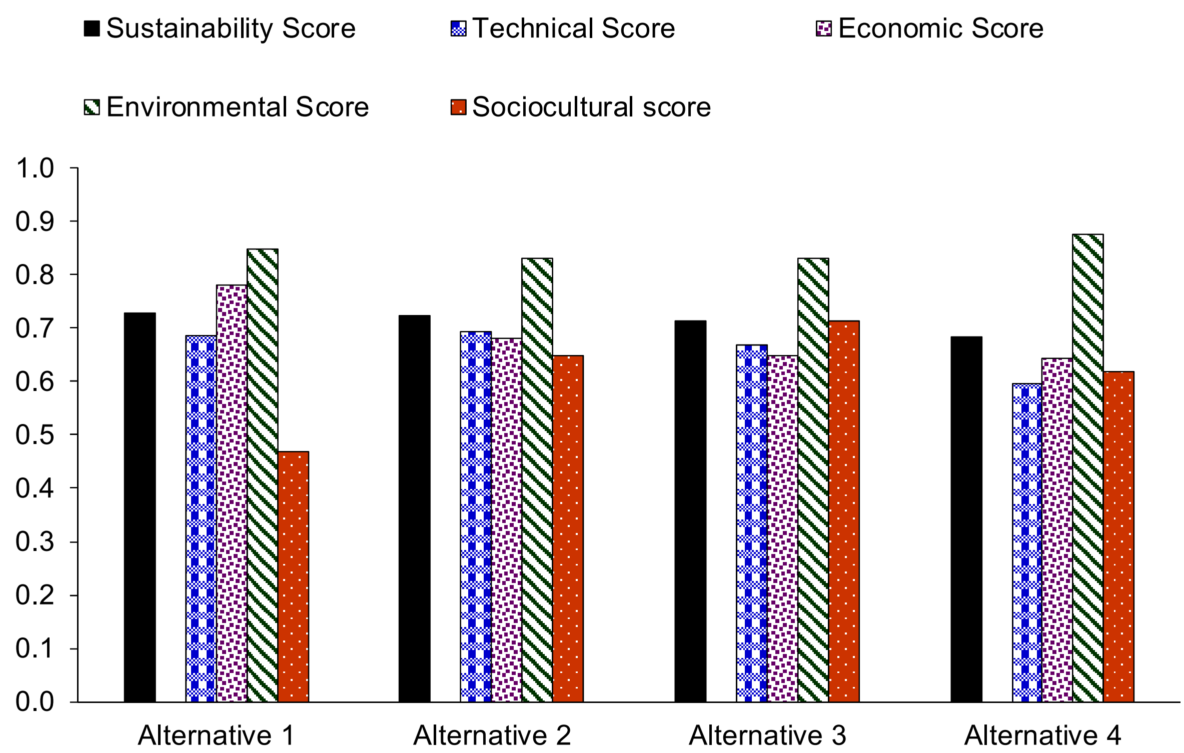

Figure 4.6 Sustainability and un-weighted criteria groups' scores of four alternatives to remove lead

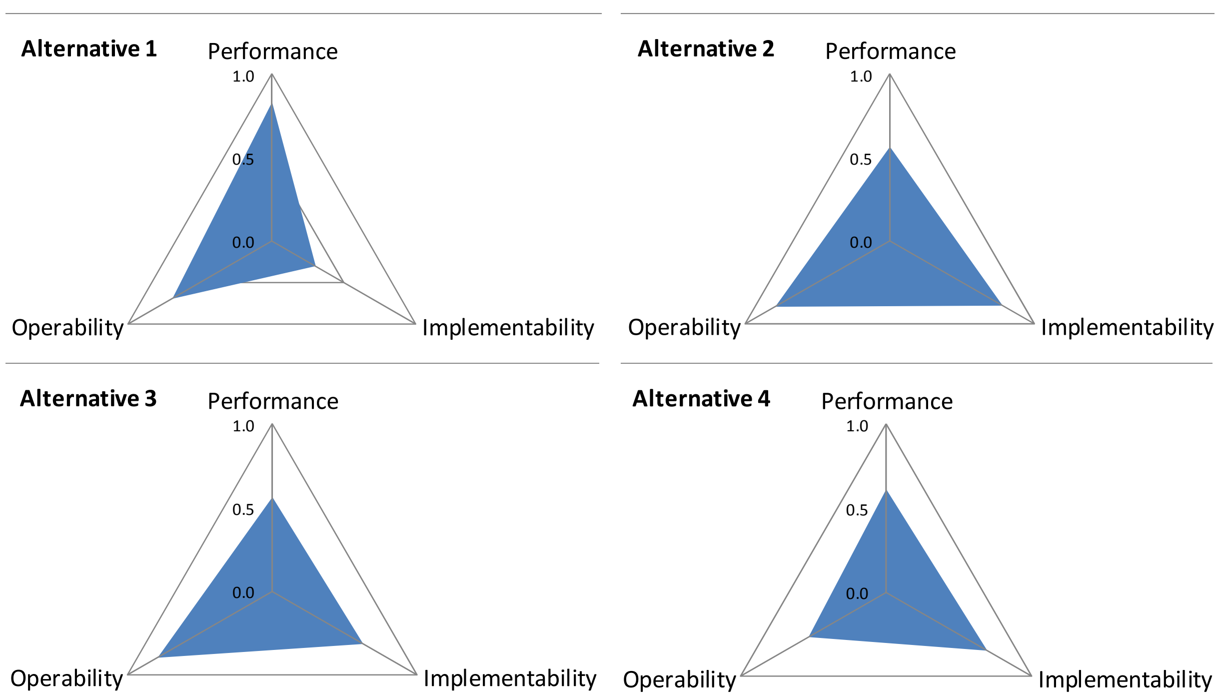

Figure 4.7 Un-weighted technical objectives' scores for four alternatives used to remove lead

4.5 Discussion and Conclusions

Sustainability is currently a core objective in any industry. The water industry is no exception especially in that it deals with a crucial and sensitive resource that is foreseen to shape the future of this planet. The water industry, especially manufacturers and water purveyors, is continuously exploring methods to integrate the concept of sustainable development into its business operations. The chapter explored a methodology for assessing sustainability with respect to a particular issue-the selection of POU/POE device-through a quantified evaluation of treatment systems characteristics.

The developed AHP-based model is intended to be a simplified and quantifiable system for operationalizing the framework of sustainability assessment of POU and POE treatment alternatives. It does so by assessing a set of 20 indicators in the form of a sustainability score. Stakeholders and decision makers can assess the comparative sustainability of a number of POU and POE alternatives. Based on the characteristics of the treatment case under study, the indicators can be evaluated and assigned normalized values. Then using the weights developed from stakeholders' surveys, final aggregated scores can be calculated to compare the various alternatives and select the more sustainable option.

The aim was to formulate a methodology for assessment of an aggregated score for comparison and selection of POU and POE water treatment systems. There were several findings from the exercise of developing this methodology:

- A balance is needed between the desire to encompass all aspects that pertain to sustainability in the selection process, and the practical challenges in calculating indicators to evaluate these aspects.
- Aggregated scores are valued for their ability to integrate large amounts of information into one value that is useful for a general or comparative judgment.
- The analytical hierarchy process is useful for structuring the selection problem, especially when the various elements of selection can be easily and logically outlined in a hierarchy.
- AHP allows for multi-level aggregation which enables in-depth analysis useful for developing sub-indices which can be used for decision reasoning.
- AHP can have some disadvantages. For example, stakeholders' surveys can be biased and subjectivity is common in the pairwise comparison process. However, such issues exist

with most multi-criteria decision analysis techniques and are unavoidable. Moreover, the consistency check that AHP provides at least alleviates one main issue-that of inconsistency-which is more than what other techniques offer.

- There can be an argument against the use of a simple weighted sum method to aggregate the score of a POU or POE alternative on the various indicators as this assumes a compensation relationship among the indicators. It is intended to couple the developed multi-criteria rating model with other decision making tools (e.g. alternative screening) to make the decision process more flexible and realistic.

The developed AHP-based selection model allows the POU and POE community to identify opportunity for improvement, by depicting areas where an alternative is lacking. The model can also be used to benchmark successful alternatives and depict elements of success. This model can also be adopted for sustainability-based selection among POU and POE alternatives to solve a particular treatment issue.

On-going work on the developed model involves an attempt to integrate it into a decision support tool to select sustainable point-of-use and point-of-entry systems. Such a tool may be used to help users, regulators, water purveyors to ensure a sustainable choice of a point-of-use and point-of-entry water treatment system.

Chapter 5

A Decision Support System to Select Sustainable Point-of-Use and Point-of-Entry Water Treatment Systems

This chapter is based on an article of the same title to be submitted for potential publication in a scientific journal on July 2011. Cited references are in the consolidated list of references at the end of thesis.

This article focuses on the integration and incorporation of two decision aid tools into the decision support system (DSS). The tools are: (1) knowledgebase screening; and (2) the sustainability rating and ranking discussed in Chapter 4. Furthermore, the article explores the various aspects of interactivity in the decision support system; focusing on three interactive modules: (1) the case entry module, (2) the knowledgebase editor module, and (3) the sustainability criteria and indicators pairwise comparison questionnaire. A case study illustrates the DSS input and output and aspects of usability of the DSS.

Summary

Point-of-Use and Point-of-Entry devices are, in some cases, considered to be a viable solution for drinking water suppliers and consumers alike to deal with site specific drinking water issues. However, due to their unique decentralized nature there are some concerns with regard to their sustainability. This article demonstrates a newly developed decision support system that employs decision making techniques to select among the various devices based on their characterization and sustainability assessment. Careful illustration of the various aspects and components of the decision support system is provided and the decision logic is explained. Aspects of validity, usability and sensitivity analysis are demonstrated through a hypothetical case study for lead removal from centrally treated drinking water. The output of the decision support system is shown to help in determining the most sustainable treatment device which should have positive implications for the application of point-of-use and point-of-entry devices.

Keywords: Analytical hierarchy process; decision support system; point-of-use; point-of-entry; sustainability

5.1 Introduction

Planners of social and economic development projects are currently faced with many challenges due to the increase in the number of factors that need to be considered in their plans. Traditionally project planning, including planning water supply projects, focused on service or product demand and the required resources to construct and operate the project's facility. Nowadays, unprecedented technical, environmental, socio-cultural, and economic factors need to be considered in project planning (Pahl-Wostl, 2007; Pahl-Wostl *et al.*, 2008). This situation is often addressed by researchers as a 'complex' situation. Complexity analysis and planning under complexity has become a current concern of the scientific and professional community. Drinking water supply is an industry that experiences many challenges, creating a "complexity" situation, these challenges include: quality deterioration of source water, financial constraints, energy constraints, emerging contaminants, contaminants introduced in the distribution system, consumer awareness and concerns, and many more challenges (MacGillivray *et al.*, 2006; Chung *et al.*, 2008).

Although many measures have been discussed to overcome complexity (Pahl-Wostl, 2007; Pahl-Wostl *et al.*, 2008) there are certain key thoughts that are used to outline the most important of these measures: (1) decentralize solutions to overcome major system failures; (2) increase redundancy to increase probability of overcoming unforeseen pressures; (3) develop and implement sustainable solutions; (4) rely on systems analysis to incorporate all the factors that may influence the planned project; and (5) preserve the knowledge acquired from previous projects and from investigations to retrieve it during future planning and evaluation. In the water supply industry, point-of-use (POU) and point-of-entry (POE) treatment represent a potential part of the solution to water supply challenges. These devices provide a decentralized and responsive solution that can, in some cases, be used on their own. In addition, when used after centralized treatment, they can also increase the redundancy or robustness of water supply systems (Pontius *et al.*, 2003; McEncroe, 2007; Chung *et al.*, 2008; Peter-Varbanets *et al.*, 2009; Hamouda *et al.*, 2010).

Recent advances in POU and POE technologies offer a wide range of decentralized alternatives to complement or in some cases replace central drinking water treatment. The commercialization of these devices has caused a dramatic increase in the number of marketed devices which leaves consumers and community water suppliers with the difficult task of choosing among them (USEPA, 2006a; Hamouda *et al.*, 2010). The certification of these devices - to standards developed by NSF International and the American National Standards Institute (ANSI) - and the numerous reports issued on the implementation and management of these devices helps considerably in selecting the most suitable treatment device. Nevertheless, when the desire to incorporate systems analysis and sustainability considerations is added to this diversity of information sources, a complex decision-making situation is created. Therefore, the need to aid consumers and stakeholders in selecting a suitable and sustainable POU or POE device is evident.

In an attempt to contribute to efforts to overcome the complexity of drinking water supply, Hamouda *et al.* (2010) developed a framework to screen and rank POU and POE alternatives based on their comparative sustainability. 'Sustainable' in this context refers to a hierarchy of parallel criteria that capture the relative fulfillment of various POU and POE treatment systems with respect to: (a) safe drinking water to help maintain good human health and hygiene; (b) minimum negative impact on the environment; (c) better use of human, natural, and financial resources; (d) a high degree of functional robustness and flexibility; and (e) cultural acceptance thus encouraging responsible behavior by the users. The knowledge generated from the systems analysis and sustainability assessment needs to be preserved and automated to be available for future drinking water supply projects that consider using POU and POE devices. Thus the selection framework needs to be incorporated into a decision support system (DSS) that can generate sustainable solutions to water treatment problems. This chapter demonstrates a completed interactive Decision Support System to aid stakeholders (such as water utilities and regulators) in Selecting Sustainable Point-of-Use and point-of-entry drinking water Treatment Systems (D4SPOUTS).

5.2 Background

Decision support systems are developed to automate assessment and present judgment. A number of DSS developers have recognized that relying solely on technical aspects does not do justice to the complexity of a water treatment problem and some have adopted a sustainability assessment approach to widen the scope of selection criteria (Hidalgo *et al.*, 2007; Hamouda *et al.*, 2009). D4SPOUTS is intended to be used in the pre-feasibility stage, when there is a desire to shortlist a number of certified POU and POE devices that represent the most suitable and sustainable solutions to a particular water treatment case. Developing a DSS requires gathering and integrating knowledge from several disciplines to ensure the success of the developed DSS (Mysiak *et al.*, 2005). Knowledge from disciplines such as computer programming, decision making theory, knowledge management, and drinking water treatment was used in developing D4SPOUTS. The process of developing D4SPOUTS went through four main phases:

1. Reviewing how decision support systems are developed, particularly outlining the stages for developing decision support systems for water and wastewater treatment processes selection and design (Hamouda *et al.*, 2009). Furthermore, it is important to ensure the interactivity of a developed DSS to make it more usable and applicable for a range of cases, and allow for its modification to suit local needs.
2. Following a systems analysis approach to outline the technical, environmental, and socio-economic drivers, constraints, and parameters involved in selecting sustainable POU and POE drinking water treatment systems (Hamouda *et al.*, 2010). The systems analysis approach was chosen to be able to trace all the relevant information for selecting a sustainable POU or POE system. The results of the analysis were the basis for developing the POU and POE systems knowledgebase and defining the characteristics and parameters that will formulate the user input, the decision making rules, and the outcome of the DSS.
3. Incorporating the results of the systems analysis in a conceptual multi-criteria decision analysis (MCDA) framework for assessing the sustainability of POU and POE alternatives (Hamouda *et al.*, 2011). Sustainability assessment using multi-criteria decision analysis (MCDA): A multi-criteria model was developed to assess the sustainability of POU and POE devices. The model is fully described in Hamouda *et al.* (2011). The model considers a number of sustainability objectives categorized under four main criteria groups (technical, economic, environmental, and sociocultural). A list of 20 indicators categorized under the four criteria group was developed and the decision parameters were formulated into categorical or mathematical equations to calculate the indicators' values. Table 5.1 shows the four criteria groups and the underlying objectives, as well as the indicators used to evaluate the sustainability of POU and POE alternatives (Hamouda *et al.*, 2011). The multi-criteria model employed the analytical hierarchy process (AHP) and a simple weighted sum of all indicators to calculate an aggregated value for a POU or POE system's sustainability.
4. Incorporating the conceptual MCDA framework in addition to other decision rules into an interactive computerized decision support system and evaluate the success of that DSS in addressing the POU and POE selection problem.

This chapter focuses on the fourth and final phase of D4SPOUTS development. The objective is to demonstrate how D4SPOUTS has structured the existing knowledge of POU and POE treatment processes as a decision support system to help consultants, water purveyors, and other stakeholders systematically through the decision process to select sustainable POU and POE devices. The system architecture also addresses knowledge transfer by making POU and POE devices models and manufacturers information readily accessible. A case study and a sensitivity analysis are used to demonstrate D4SPOUTS usability and validity.

Table 5.1 Description of socio-cultural sustainability indicators and methods of evaluation

Criteria Groups	Objectives	Focus of the Indicators
Technical	Maximizing performance	Assessing system's incidental effect, reliability (redundancy), robustness, microbial regrowth risk
	Maximizing implementability	Assessing the skill required to install the system and the area and volume it occupies (footprint)
	Maximizing operability	Assessing the skill required to operate and maintain the system and frequency of maintenance
Environmental	Minimizing resource consumption	Assessing resource consumption (energy and chemical use)
	Minimizing environmental footprint	Assessing and the amount and hazardousness of solid and liquid residuals produced by the system
Economic	Minimizing life cycle cost	Assessing capital cost, operating and maintenance cost, and potential savings with bulk purchases
Socio-cultural	Maximizing consumer acceptance	Assessing consumer acceptance of the aesthetics of the produced water, the system's configuration, and the system's attractiveness and interactiveness
	Maximizing product availability	Assessing the availability of the system in the market in terms of: (1) availability of the system through different sales methods (2) number of certified systems with the same treatment train

5.3 D4SPOUTS Decision Logic

Determining the decision logic that best fits the purpose of the decision making process is a critical task in developing a DSS. The purpose of D4SPOUTS is to shortlist feasible POU and POE alternatives that are suitable for a particular water treatment case, and then outline the more sustainable alternatives for the user to select from. Figure 5.1 illustrates the decision logic that D4SPOUTS is based upon. The decision logic simply outlines the information requirements and processing that set the scene for the actual design and automation of D4SPOUTS. Microsoft Excel® was used to translate the decision logic into a fully automated interactive DSS. The decision logic for D4SPOUTS has the following characteristics:

1. At the core lies the purpose of D4SPOUTS, represented by the output in the form of a sustainability ranked list of POU and POE devices. This output has to come as a result of three essential inputs:
    a. The characteristics of the case under analysis which will influence the selection process. The characteristics include: basic information on the community or facility being considered; the source water type, quality, and target contaminants; and the available resources and operating conditions for the treatment device.
    b. The characteristics of the POU and POE devices available as alternative solutions which will influence the appropriateness of the device as a potential solution to the case under analysis as well as its sustainability score. The characteristics include: basic information about the device manufacturer and model; some operating constraints for the device; certification information for the device to NSF/ANSI standards; and other device characteristics that are needed to calculate its sustainability score.
    c. The reasoning or decision making process that transforms all the information into a relevant and valid output. In D4SPOUTS the decision making is a two-step process where the devices are first screened using Pass/Fail screening rules that are triggered by both the case and the device characteristics; followed by the evaluation of the MCDA sustainability scores for the screened list and ranking them accordingly.

2. On the fringes lie the tools that feed the core system with the necessary information. These tools are explained in the following section and they include: a knowledge acquisition tool (a user interface) that is used to harness user input, a POU and POE devices knowledgebase that stores the various information in a specific format allowing its effective use in decision making, and decision modules that supply the screening rules and sustainability rating mechanism used in decision making.

3. The ties in Figure 5.1 represent the elements of interaction in D4SPOUTS. As will be explained later, the user input was designed to influence all the information used in D4SPOUTS decision logic. This was an important objective in the design process to ensure the usability of D4SPOUTS.

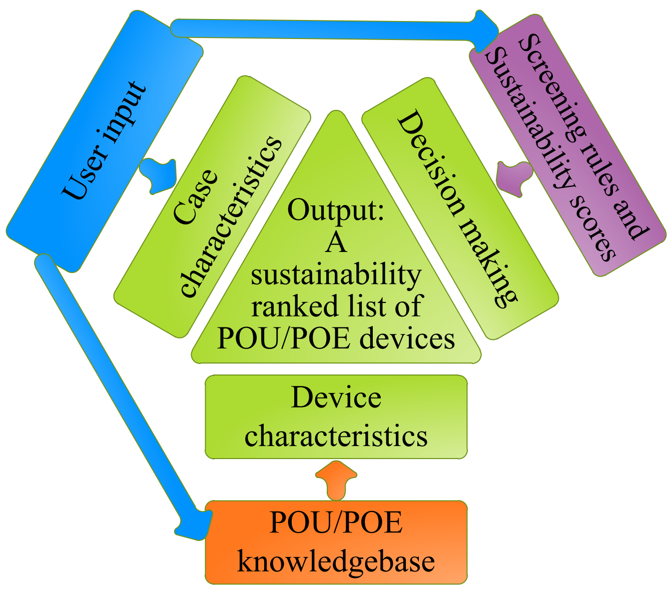

Figure 5.1 D4SPOUTS decision logic

5.4 D4SPOUTS Components and Data Flow Illustrated by a Case Study

The superstructure of the D4SPOUTS includes three main components (Figure 5.2): (1) multiple user interfaces, (2) a knowledgebase containing heuristic and numerical characterization of POU and POE devices; including modules to quantifying sustainability indicators, screen alternatives, and rate and rank devices based on sustainability, and (3) an output module. Figure 5.2 illustrates the interaction and data flow between these components that are described in the following sub-sections. For the purpose of an effective illustration of D4SPOUTS, a hypothetical case study is discussed below.

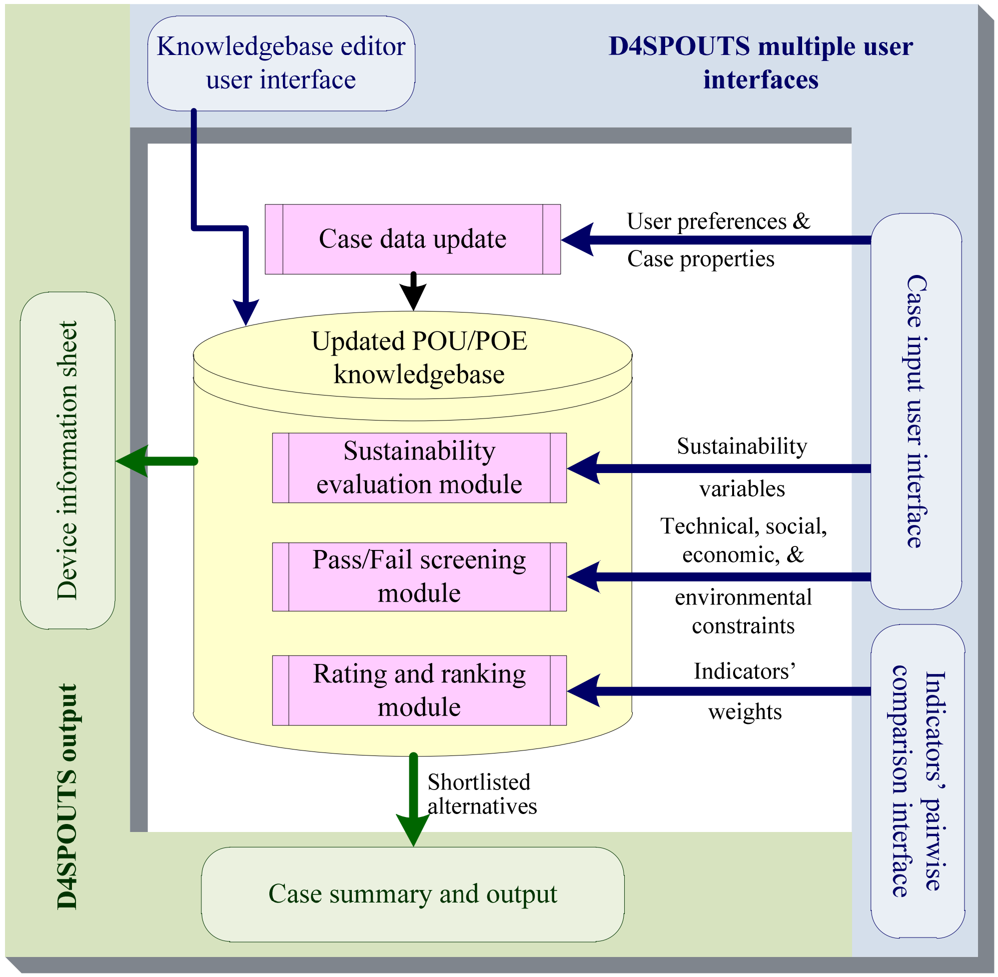

Figure 5.2 D4SPOUTS components and data flow

5.4.1 Multiple User Interfaces

D4SPOUTS is designed to allow users to manipulate any of the data used in the decision logic. There are three user interfaces that allow for separate user input. D4SPOUTS starts with a welcome screen (Figure 5.3) where the user identifies which input interface to run. The first input interface is for case input, the interface is composed of 5 pages:

1. Case information page (Figure 5.4): includes general case information such as: case name, organization name, state or province, community name, source water type (centrally treated, surface, deep ground water, shallow ground water, or rain water), consumer health (normal or immunocompromised), facility type (residential, commercial, educational, or health), and community type (rural or urban).

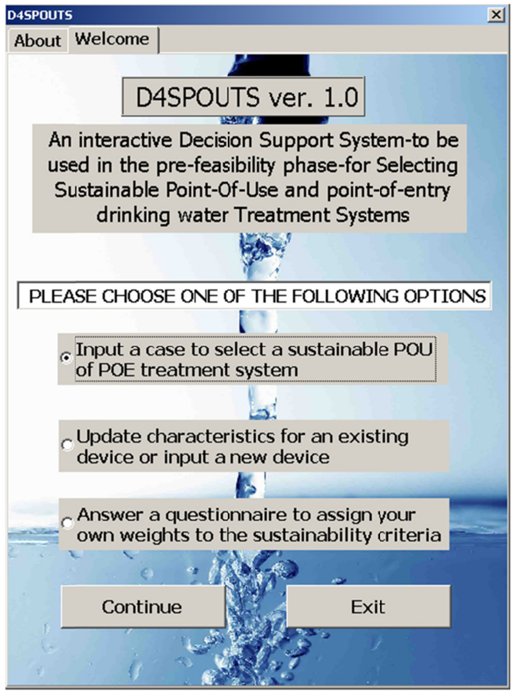

Figure 5.3 D4SPOUTS welcome screen

2. System operation page (Figure 5.4): includes specific system operation information that may represent constraints on the type of device selected, such as: operating pressure, water temperature, number of units to be installed, available funds, required flow, available space, availability of electric supply, and the type of sewer management system (domestic sewer, septic tank, or tile sewer).

3. Source quality page (Figure 5.4): includes information on the quality of water to be treated by the device, it includes identifying a number of contaminants' concentrations that may affect a device's operation (e.g. hardness) as well as a categorized list of contaminants that the device is intended to remove (aesthetic parameters, metal contaminants, volatile organic contaminants, other chemical contaminants, and disinfection requirements). The list of contaminants was populated using NSF/ANSI standards used to certify POU and POE devices (Standards 42, 44, 53, 55, 58, and 62).

4. Device preferences page: includes a list of options a user can select to specify a preferred device configuration (there are 8 configuration types specified by NSF), a treatment train (a sequence of processes that a device can be composed of), a manufacturer, or a device model.

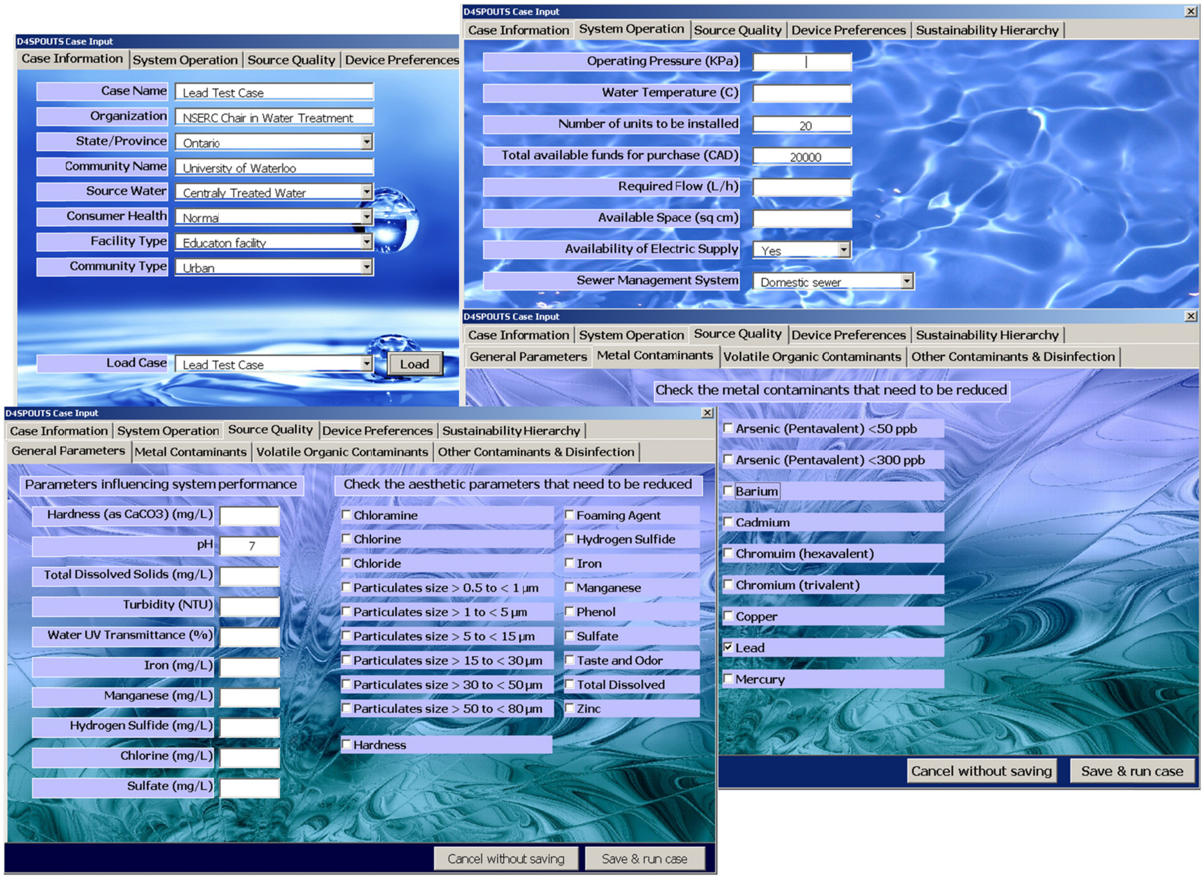

Figure 5.4 Case input interface

5. Sustainability hierarchy page (Figure 5.5): includes a display of the hierarchy of indicators, objectives, and criteria groups and their relative weights. D4SPOUTS gives the option of either using the default weights that were a result of a questionnaire response by 19 stakeholders (Hamouda *et al.*, 2011), or using user defined weights that are a result of the response to a built-in pairwise comparison questionnaire which is the third user interface described later.

The case study used is illustrated in Figures 5.4 and 5.5. The case requires 20 devices to be installed at an educational facility to remove lead from centrally treated water. The available funds for this project are 20,000 CAD and other characteristics include: normal consumer health (i.e. no immunocompromised), domestic sewer system, and an urban setting. No additional preferences or constraints were specified and default weights were used to calculate the sustainability scores (Figure 5.5). This case study is an example of a typical use of D4SPOUTS. A different kind of use for the case user interface is when a user has a POU/POE device already installed and wants to examine if it can successfully remove a target contaminant. In this case a user would select the manufacturer and model of the device installed on the preferences page, and run D4SPOUTS to check if the device fulfills the required task.

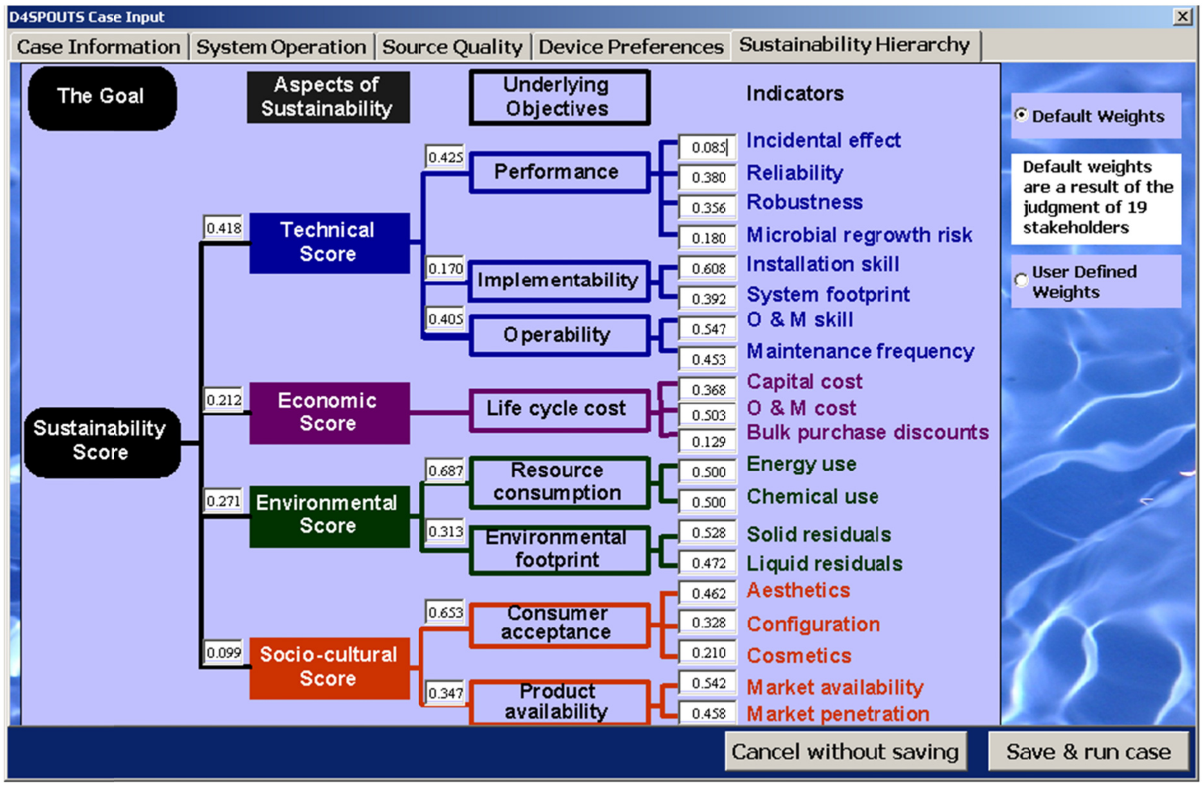

Figure 5.5 Sustainability hierarchy in the case input interface

The second user interface is a knowledgebase editor that users, particularly manufacturers, can use to input new POU and POE devices or change the characteristics of devices that already exist in the knowledgebase. The interface has four main pages (Figure 5.6):

1. General characteristics and constraints page: includes information on the device's manufacturer, model, country of manufacture, picture, and operation constraints (e.g. minimum operating pressure, or maximum operating concentrations of iron, manganese, etc.).

2. Specific characteristics page: includes information that is commonly used to calculate the values of sustainability indicators such as: device's energy consumption, installation skill required, configuration type, treatment train, and number of replacement components.

3. NSF certification page: includes information on which NSF/ANSI standards are the device certified for and the specific contaminants which the device is claimed to reduce.

4. Sustainability indicators page: includes an explanation of how each indicator is calculated and information that is specific for calculating an indicator.

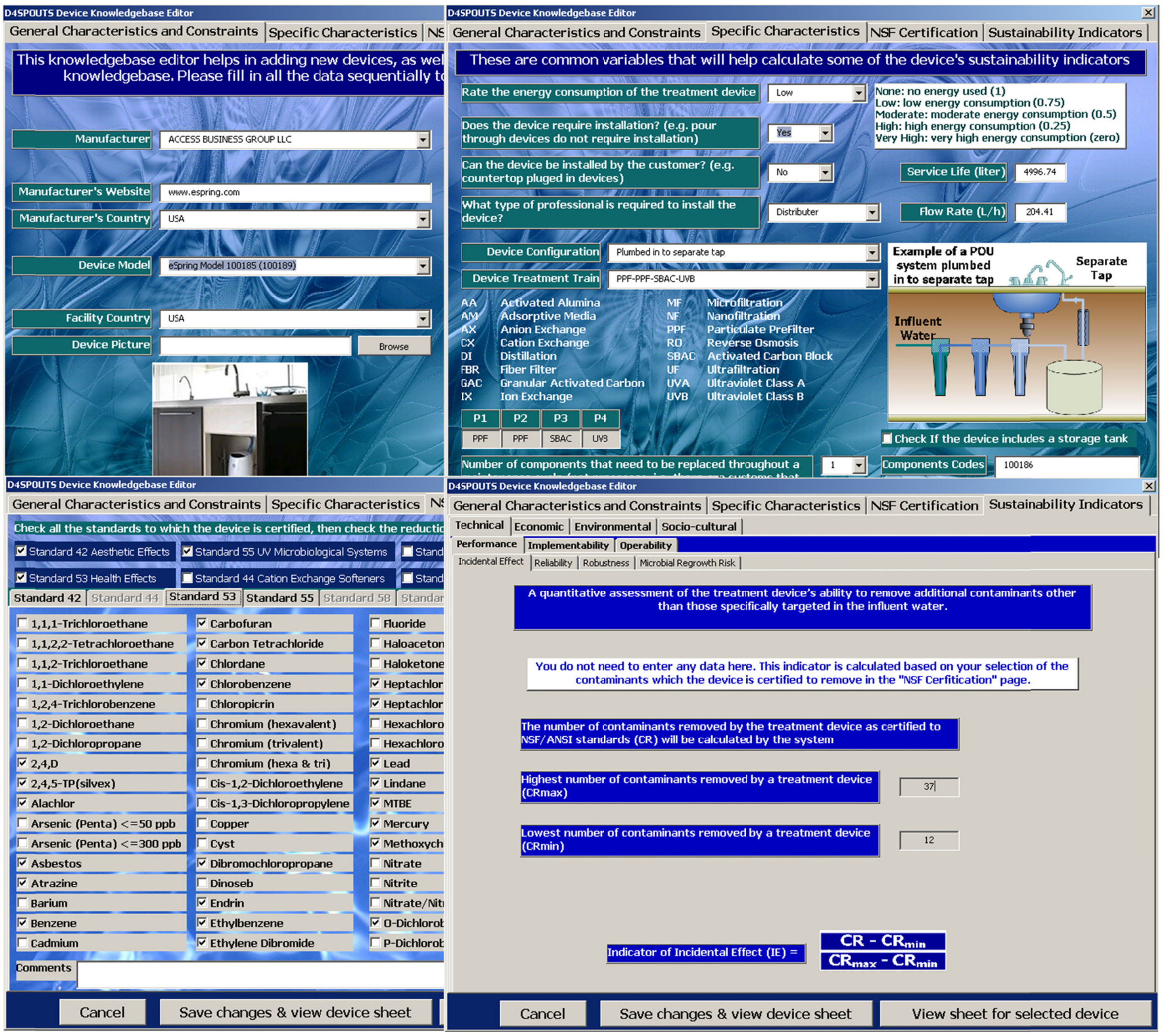

Figure 5.6 Knowledgebase editor user interface

The third user interface is a questionnaire that user can use to assign relative weights to the sustainability indicators, objectives, and criteria groups. Establishing the relative importance of each indicator is essential for aggregating a sustainability score. The questionnaire employs the pairwise comparison method which is an Analytical Hierarchy Process (AHP) technique for developing relative weights (Lai *et al.*, 2008; Saaty, 2008). The user is asked to select a circle that represented the relative importance between two indicators based on Saaty's scale (Figure 5.7). In Saaty's scale, a judgment that two indicators are equally important is a score of 1, moderately more important 3, strongly more important 5, very strongly more important 7 and extremely more important 9. The interface also checks for the consistency of the input pairwise comparison and requires that the user revise the input if the results are inconsistent. The pairwise comparisons result feeds into another calculation sheet that employs matrix algebra to calculate the relative weights based on the user's response (Hamouda *et al.*, 2011). The user has the option to either use the weights developed based on the questionnaire response (user defined weights) or to use the built-in default weights that are a result of the response of 19 stakeholders of POU and POE treatment to the same questionnaire (Figure 5.5).

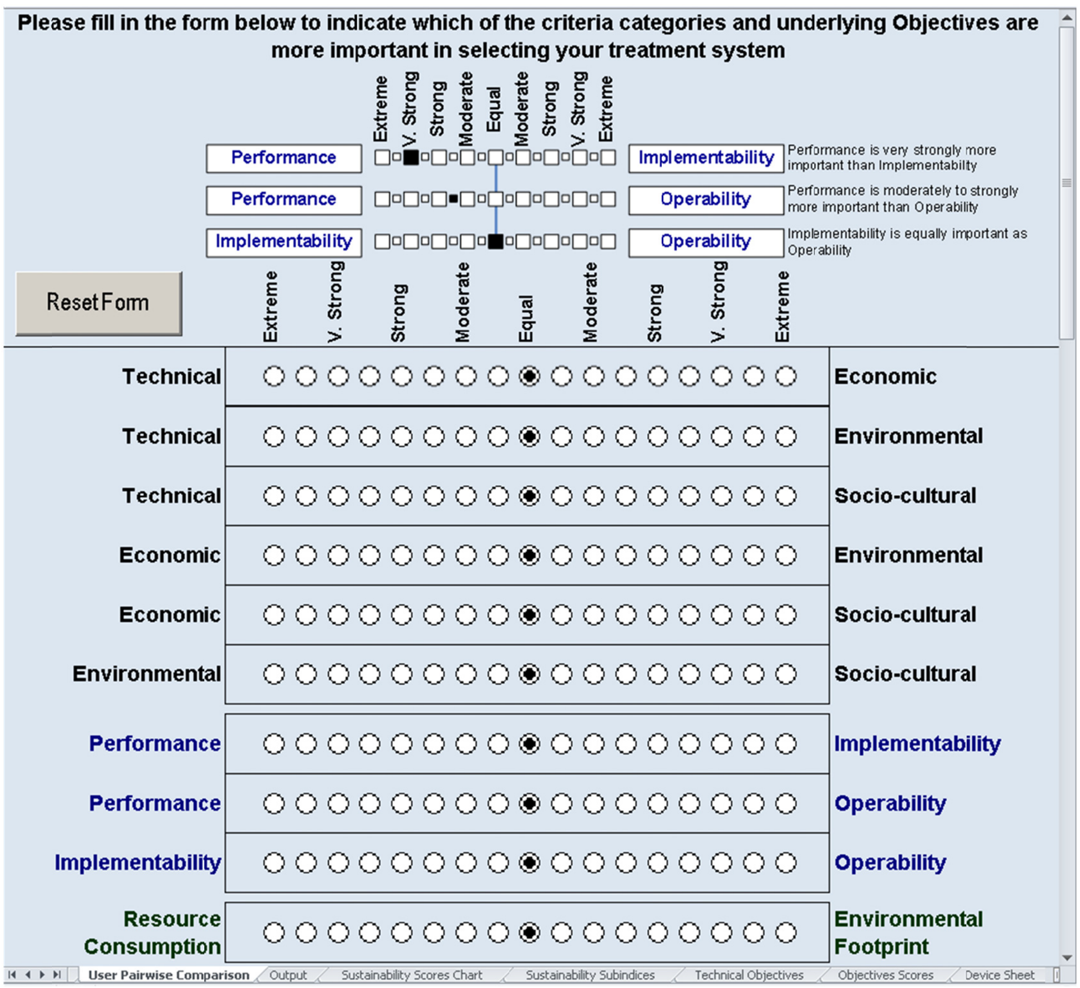

Figure 5.7 Sustainability indicators user pairwise comparison interface

5.4.2 POU and POE Knowledgebase

The knowledgebase is the second main component of D4SPOUTS. Figure 5.2 illustrates how the knowledgebase is at the core of D4SPOUTS and that it includes three critical modules that constitute the 'brain' of D4SPOUTS, namely: the sustainability evaluation module, the Pass/Fail screening module, and the rating and ranking module. The knowledgebase is a large worksheet in the Excel® based DSS with around 750 columns of data relevant to the three modules. All the user input from the previously explained user interfaces lead to the update of the data in the knowledgebase, making it ready to feed into the output of D4SPOUTS. Since D4SPOUTS is intended to comprehensively address the issue of selecting sustainable POU and POE devices, it strived to include as many parameters as possible in the sustainability assessment and the selection process. This consequently requires numerous data to be gathered for each device to have a full description that allows for proper assessment. The required data was not readily available, thus currently the knowledgebase only has a small number devices with complete information to allow for screening and sustainability evaluation. This is the main reason why the knowledgebase editor was developed, to allow more devices to be added and ensure their proper characterization. However, the existing knowledgebase is sufficient to illustrate the application of D4SPOUTS.

The sustainability evaluation module uses data from the knowledgebase editor and from the case input user interfaces to calculate the values for the 20 sustainability indicators (Table 5.1 and Figure 5.5). The Pass/Fail screening module then triggers a number of rules to check if any of the devices in knowledgebase fails to satisfy any of the constraints set for the case under analysis. Table 5.2 shows a list of constraints and the corresponding device characteristic that is required for the device to pass the screening rule used in the screening module.

The rules help reduce the number of alternatives such that only feasible alternatives that pass all the screening rules are then run through the rating and ranking module. This final module evaluates the objectives scores and the aggregated sustainability score using the weights (*w*) specified by the user earlier (user defined or default weights). The aggregation is based on a simple weighted sum equation:

$$SustainabilityScore = \sum_{groups} w_{criteria.group}\left[\sum_{objectives} w_{objective}\left(\sum_{indicators} Value_{indicator} \times w_{indicator}\right)\right]$$

Table 5.2 D4SPOUTS constraints and respective required device characteristics

Constraint definition	Required device characteristic
Target contaminants exist in the source water	Has reduction claims for the target contaminants
Source water is untreated or consumer is immunocompromised	Has multiple treatment processes (multi-barrier approach) with disinfection
Source water concentrations of hardness, iron, manganese, hydrogen sulfide, sulfate, chlorine, TDS, or turbidity	Has maximum operating concentration higher than the source concentrations
Source water operating pressure, temperature, or UV transmittance	Has operating window (min to max) that envelopes the source water values
Specified available funds, space, and required flow	Has footprint, purchase cost, and flow that satisfies requirements
No reliable source of electricity	Does not require electricity for operation
User preferred configuration type, manufacturer, treatment train, or device model	Has a matching configuration type, manufacturer, treatment train, or device model

The case study that was entered only triggered one screening rule, that which considered contaminant reduction claims. Out of the few devices in the knowledgebase, only 4 devices removed lead and thus only these 4 were considered among the feasible devices. After all the feasible devices are rated and their sustainability scores are calculated, the knowledgebase automatically sorts all the feasible devices based on their sustainability scores in a descending order. The results are now ready to be copied to D4SPOUTS output.

5.4.3 D4SPOUT Output

A decision support system's output should provide information that serves its purpose. D4SPOUTS has two output modules. The first output module is presented to the user when a device is entered, updated, or selected by the user in the knowledgebase editor. The module is also set to show the details of the top device in the shortlisted results from a case run. The device characteristics information sheet (Figure 5.8) provides a summary of all the characteristics of a device entered through the knowledgebase editor. In addition, it displays the sustainability scores of that device from the latest case run. This type of output can be useful to users requiring details on devices being considered for pilot study or for purchase and installation. Figure 5.8 shows an example of the device characteristics information sheet for one of the 4 devices that were shortlisted by D4SPOUTS to remove lead from centrally treated water.

The second output module is specifically designed to present the user with a summary of the case and a series of illustrations to help in outlining the differences between the 4 top rated devices in the shortlisted alternatives. Figure 5.9 shows the case summary and output sheet. The case summary offers an executive report of the case under analysis which includes: most of the information from the case user interface; a shortlist of the 6 top rated devices and their sustainability objectives, criteria groups, and sustainability scores; and some details for the top 3 devices. This type of summary report is useful for users who require a simple recommendation as to which device to choose, without having to understand the reasons for the recommendation. The user can simply select one of the top ranked devices.

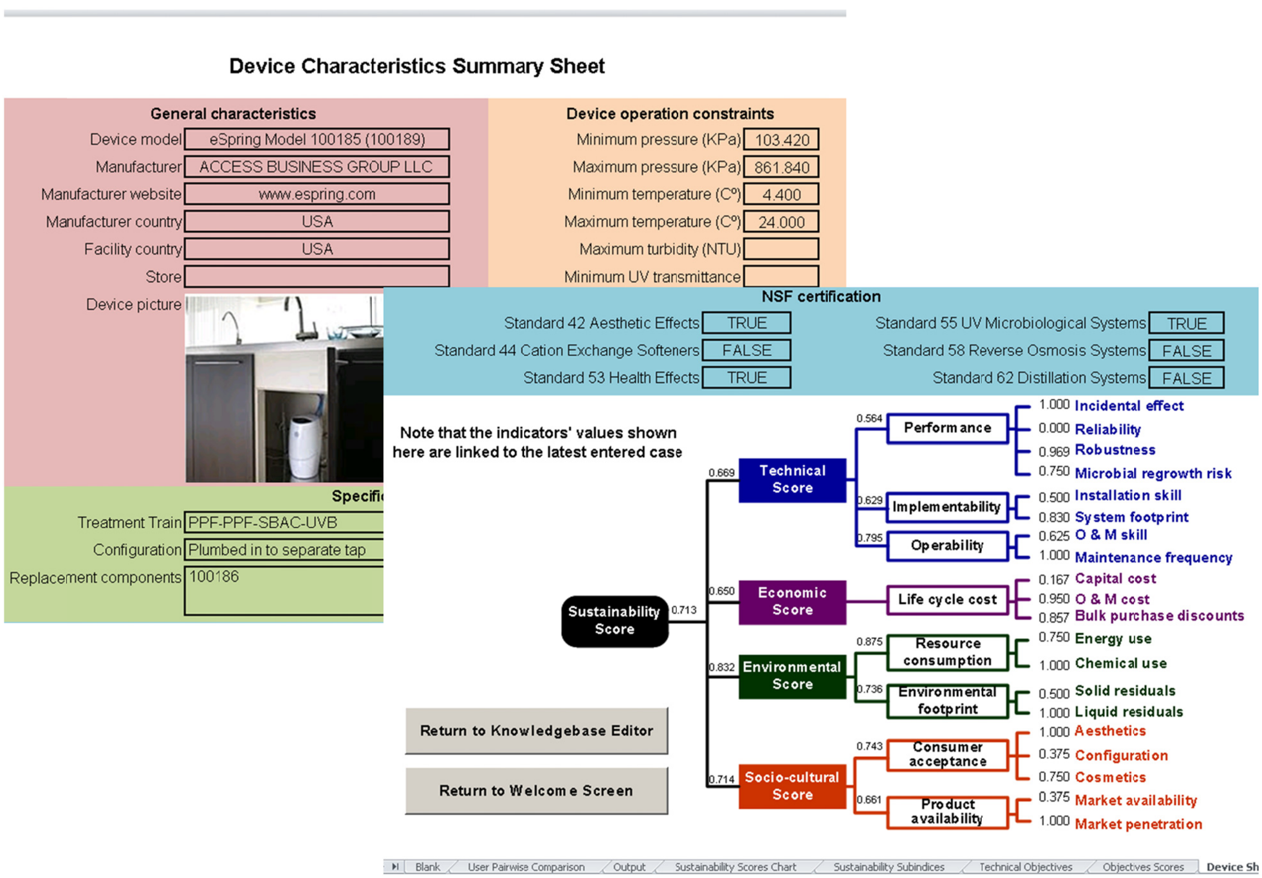

Figure 5.8 Device characteristics summary sheet

Case Summary and D4SPOUTS Output

General characteristics		Preferences and constraints		Source Quality	
Case Name	Lead Test Case	Number of units	20	Water temperature (C°)	N/A
Organization	NSERC Chair in Water Treatment	Total available funds (CAD)	20,000.00	pH	7.0
State/Province	Ontario	Required flow (L/h)	N/A	Hardness	N/A
Community Name	University of Waterloo	Available space (sq cm)	N/A	TDS (mg/L)	N/A
Source Water	Centrally Treated Water	Operating pressure (Kpa)	N/A	Turbidity (NTU)	N/A
Consumer Health	Normal	Preferred configuration	N/A	Iron (mg/L)	N/A
Facility Type	Education facility	Preferred manufacturer	N/A	Manganese (mg/L)	N/A
Community Type	Urban	Preferred device	N/A	Hydrogen sulfide (mg/L)	N/A
Type of sewer system	Domestic sewer	Preferred treatment train	N/A	Sulfate (mg/L)	N/A

Shortlist of point-of-use and point-of-entry devices that are suitable solutions for this case

Device Model	Max performance	Max implementability	Max operability	Min LCC	Min resource consumption	Min env. footprint	Max consumer acceptance	Max product availability	Technical Score	Economic Score	Environmental Score	Socio-cultural Score	Sustainability Score
PNRQ15FBL	0.832	0.304	0.695	0.782	1.000	0.514	0.380	0.635	0.687	0.782	0.848	0.469	0.729
eSpring Model 100185 (100188)	0.564	0.781	0.795	0.681	0.875	0.736	0.643	0.661	0.694	0.681	0.832	0.649	0.724
eSpring Model 100185 (100189)	0.564	0.629	0.795	0.650	0.875	0.736	0.743	0.661	0.669	0.650	0.832	0.714	0.713
GNSV70RBL	0.613	0.696	0.535	0.645	1.000	0.604	0.611	0.635	0.596	0.645	0.876	0.620	0.684
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Details for the three top rated devices

PNRQ15FBL		eSpring Model 100185 (100188)		eSpring Model 100185 (100189)	
Manufacturer	General Electric Co.	Manufacturer	ACCESS BUSINESS GROUP LLC	Manufacturer	ACCESS BUSINESS GROUP LLC
Treatment train	SBAC-RO-SBAC	Treatment train	PPF-PPF-SBAC-UVB	Treatment train	PPF-PPF-SBAC-UVB
Configuration	Plumbed in to separate tap	Configuration	Countertop connected to faucet	Configuration	Plumbed in to separate tap
Store	N/A	Store	Home Depot	Store	Home Depot
Website	www.geappliances.com	Website	www.espring.com	Website	www.espring.com
Purchase cost (CAD)	390.00	Purchase cost (CAD)	950.00	Purchase cost (CAD)	950.00
Replacement cartridge	FQROMF	Replacement cartridge	100186	Replacement cartridge	100186

Figure 5.9 A sample case summary sheet and output

To understand the reasons behind the recommendations suggested by D4SPOUTS, more illustrations were developed to reveal underlying characteristics influencing the decision. Figure 5.10 shows radar diagrams for the sustainability criteria groups' scores of the top 4 devices. The diagram has 4 axes representing the 4 criteria groups; each ranging from 0 to 1. The point where the axes meet corresponds to a value of 0—the lowest score in terms of sustainability. The highest value of 1 represents the highest score in terms of sustainability. The device's score in each criteria group is plotted on its corresponding axis then a polygon is formed by joining the scores on the 4 axes. The radar diagram shows the device scores without considering the criteria groups' weights. For example, even though the device model PNRQ15FBL was ranked at the top of the devices, it is clear from the figure that it is weak in terms of socio-cultural sustainability. This insight into the underlying criteria groups' sustainability scores may influence the user's decision by relying on visual judgment which is not obscured by aggregation techniques.

This abstract display of scores without considering weights is further expanded in Figure 5.11 which displays a complete picture of the comparative sustainability of the devices and their fulfillment of the sustainability objectives ignoring their relative weights. This provides the user with more information that can help in justifying the results. Furthermore, a user may choose to rely on these abstract values instead of the aggregated scores in selecting the device to install.

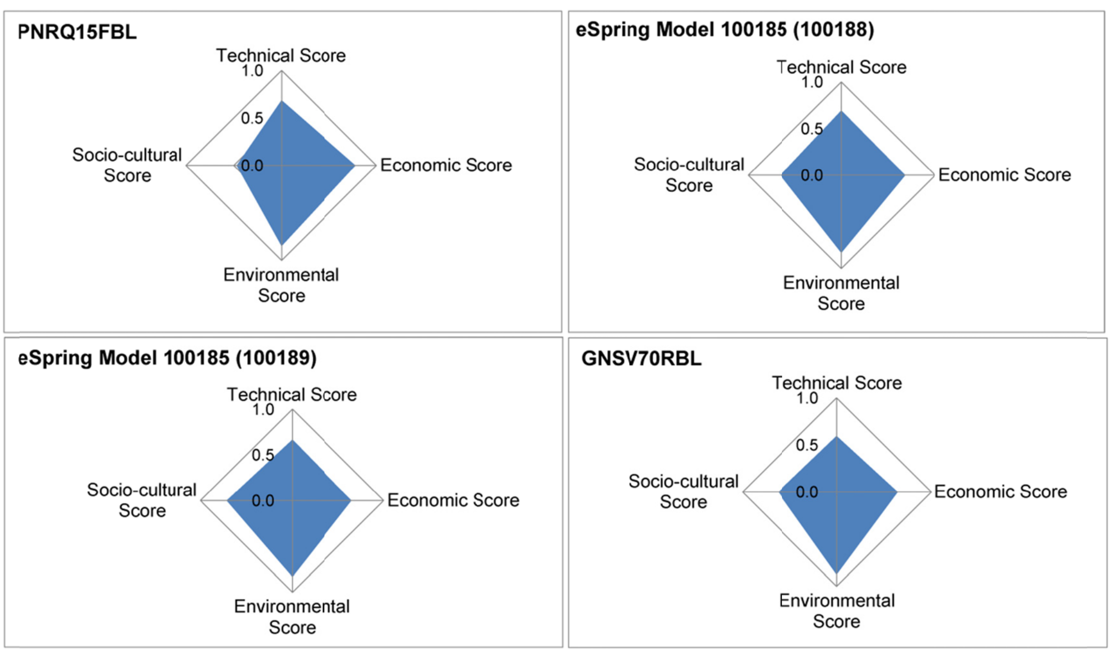

Figure 5.10 Sustainability and group scores for the four top ranked POU and POE alternatives in the sample case summary

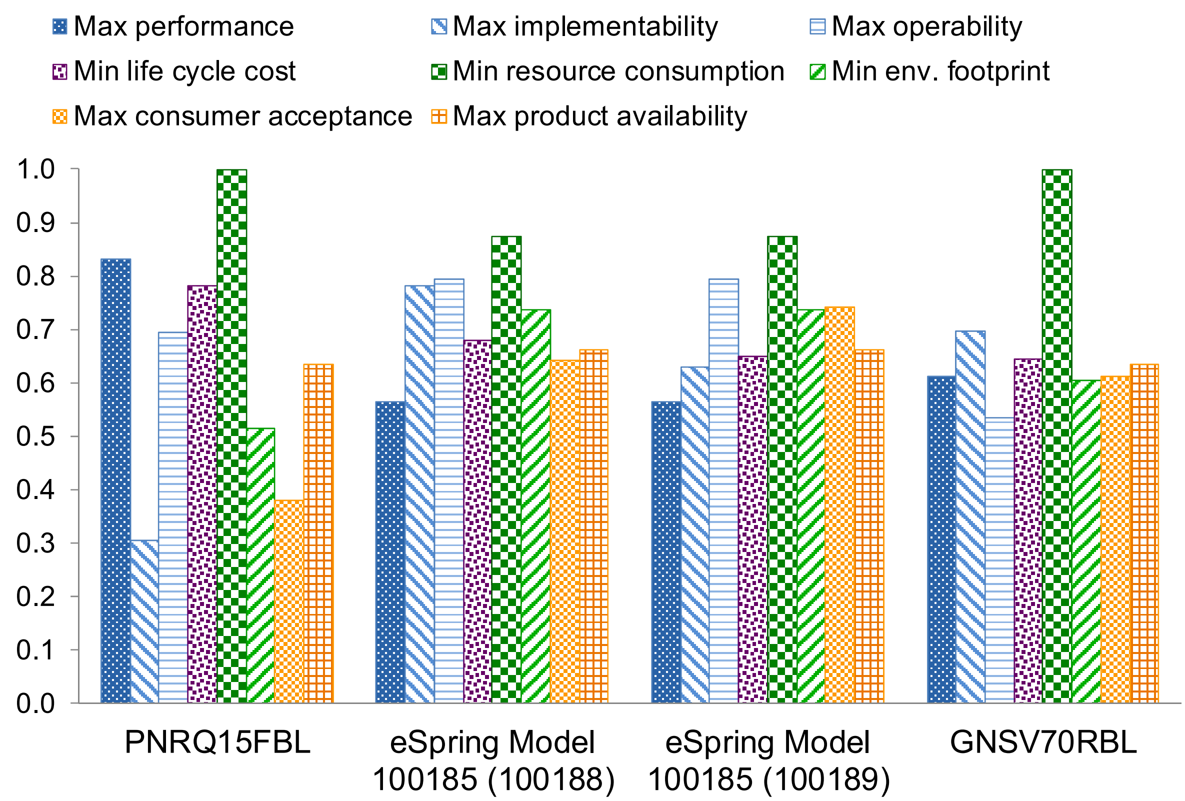

Figure 5.11 Sustainability objectives' scores for the four top ranked POU and POE alternatives

5.5 Aspects of Usability of D4SPOUT

Ease of use is the clear divide between DSSs that end up being successful in the market and those that are destined to remain on the shelf forever. There are many aspects of DSS usability and success discussed in the literature (Denzer, 2005; Mysiak *et al.*, 2005; Hamouda *et al.*, 2009). There are a number of aspects that contribute to a DSS's usability: (1) the validity of the output; (2) the user-friendliness of the DSS's interface and output; and (3) the sensitivity of the outcome to input changes (Heller *et al.*, 1998).

Evaluating the validity and usefulness of D4SPOUTS is difficult for two reasons: (1) lack of benchmarks: although there are numerous POU and POE devices installed, there has been little effort in quantifying the sustainability of these devices and standardizing the selection of suitable devices; and (2) missing values and an incomplete knowledgebase: completing the list of POU and POE devices and their full characterization using the developed knowledgebase editor is an essential step that has to precede the proper evaluation of D4SPOUTS. For the DSS to be of the full value that it can be it needs to be fully populated and this requires the participation of suppliers and disclosure of information which may not be available in product information literature or manuals. However, one factor that supports the validity of D4SPOUTS is the involvement of POU and POE stakeholders in the early development phases through the questionnaires investigating the relevance of the sustainability indicators and their relative importance to the selection of sustainable devices. Another factor is the appropriateness of the decision logic followed by D4SPOUTS.

Special attention was given to the user-friendliness of D4SPOUTS to enhance its level of interactivity. In general, the user interface should encompass aspects of user input, decision analysis and reasoning, in addition to demonstrating the DSS calculations and allowing user intervention to change decision parameters. D4SPOUTS is intended for practical use and thus a great deal of focus was put in the ability of the user to interact with it. Interactivity includes: the ability to influence the decision process, set constraints that reflect the user's preferences, set relative weights to sustainability indicators, and giving warning messages if any required information is missing. The user interface integrates the various underlying modules of D4SPOUTS to avoid the deleterious effect of having to alternate between different modules on system usability. The usefulness of D4SPOUTS output is evident in its design to provide not only the basic result of the shortlisted devices of highest sustainability rating, but also information that helps in the understanding of the reasoning behind the result, such as: case parameters, device cost and characteristics, and illustrations that allows for comparing between the top listed devices.

Although a rigorous evaluation of D4SPOUTS is not yet attainable, a simple exercise was applied to at least assess its sensitivity. D4SPOUTS performance was verified by going through the typical process of program debugging, error analysis, and data input and output analysis (Heller *et al.*, 1998; Bick and Oron, 2005). Furthermore, the sensitivity of the devices' ranking to variations in indicators' relative weights was investigated by altering the user defined indicators pairwise comparisons (Figure 5.7). Results are given in Table 5.3. The first case uses the built-in default weights of D4SPOUTS which reflect the desire to maximize technical sustainability while maintaining an acceptable level of economic and environmental sustainability, but with little regard for socio-cultural sustainability. The sustainability scores shown for the top ranked device reflect this preference.

In the second case (Table 5.3) all criteria categories are equally weighted attempting to go beyond technical sustainability, which typically involves increasing cost and is evident when the economic score of the top ranked device is compared to that from the first case (0.65 vs. 0.78 out of a maximum of 1.00). The scores thus reflect the trade-offs between conflicting criteria. The third case assumes technical compliance is the main concern and gives no weight to other technical or economic sustainability but focuses on environmental and socio-cultural sustainability. With environmental criteria being the most important, technical performance ought to only be satisfied, not exceeded, and under these constraints the bottom ranked device from the first case becomes the top ranked device. Comparisons of the criteria group scores of these three cases indicate that user pairwise comparison, which assigns weights, greatly influences the outcome of D4SPOUTS, which shows that the outcome is tailored to user requirements. Thus D4SPOUTS satisfies an important function of a DSS, which is the ability to produce case sensitive outcome.

Table 5.3 Demonstration of the sensitivity analysis of D4SPOUTS by changing weights of 4 main aspects of sustainability

	Case 1		**Case 2**		**Case 3**	
Technical weight	0.42		0.25		0.00	
Economic weight	0.21		0.25		0.00	
Environmental weight	0.27		0.25		0.70	
Socio-cultural weight	0.10		0.25		0.30	
Device rank	1st	4th	1st	4th	1st	4th
Device model	PNRQ15FBL	GNSV70RBL	eSpring 100185 (100189)	GNSV70RBL	GNSV70RBL	PNRQ15FBL
Sustainability score	0.729	0.684	0.716	0.684	0.799	0.734
Technical score	0.687	0.596	0.669	0.596	0.596	0.687
Economic score	0.782	0.645	0.650	0.645	0.645	0.782
Environmental score	0.848	0.876	0.832	0.876	0.876	0.848
Socio-cultural score	0.469	0.620	0.714	0.620	0.620	0.469

5.6 Conclusions

Increasing attention to POU and POE treatment not only raises the importance of device selection but also increases the significance of having a simple and effective decision making tool to make such decisions. For stakeholders without the necessary expertise in POU and POE systems, finding a sustainable POU or POE alternative could be quite challenging, thus making the DSS presented herein an extremely useful problem-solving tool for stakeholders. The purpose of D4SPOUTS is to help water purveyors, and other stakeholders to obtain “a short list of the most sustainable solutions” for a given problem without having to familiarize themselves with the mathematical complexities associated with the model or the solution method.

An important finding from this research is that to reduce the problem to one of shortlisting sustainable POU and POE devices requires the full intertwining of the characterization of devices and the case for which the treatment is required. D4SPOUTS successfully incorporated this capability by taking the user’s preferences and constraints and the device’s performance and limitations into account. Furthermore, the operational features of D4SPOUTS are quite user-friendly and involve a series of interactive steps to input the data as well as illustrations to enhance interaction with the user. In order to improve its usefulness, D4SPOUTS has been designed to have an efficient interface with Microsoft® Excel®.

Some of the main strengths of D4SPOUTS are:

1. It provides comprehensive decision analysis and support;
2. The design of the user input can help users think about decisions in a structured and systematic way;
3. The interface allows the user to input cases, devices, and even influence the decision logic.
4. It allows the user to thoroughly explore the shortlisted alternatives and gain a better understanding of the decision reasoning; and
5. It illustrates the fulfillment of the shortlisted devices to the varying decision objectives.

D4SPOUTS is envisioned to help make an informed decision based on sustainability analysis of alternatives POU and POE devices. This is important in the market-based industry of POU and POE treatment, especially when sustainability issues are looming. The continuous enhancement of D4SPOUTS can also help making it part of the industry’s future development by convincing manufacturers to target improving of POU and POE devices’ sustainability in their product development strategies. For example, D4SPOUTS could be adopted by an arm’s length association or organization to fully populate it with information and advertise it as a useful tool for selecting sustainable devices.

Chapter 6
Summary, Conclusions, and Recommendations

The goal of this research was to develop a decision support system to help in the selection of a sustainable point-of-use or point-of-entry treatment device to solve a particular drinking water problem. The research is intended to be a comprehensive analysis of the scope of implementing POU and POE treatment devices. The developed decision support system (DSS) will assist drinking water policy-makers, water purveyors, and consultants in selecting sustainable POU and POE treatment systems. Furthermore, it is expected that this work can successfully help in standardizing the process of selecting suitable and sustainable POU and POE devices.

The process of creating D4SPOUTS involved four main phases. The first phase included investigating how decision support systems are developed, particularly outlining the stages for developing decision support systems for water and wastewater treatment processes selection and design (Chapter 2). The review helped outline the framework for developing D4SPOUTS, pointing the way to systems analysis as the first and most critical step to fully define the problem. It also pointed out the importance of ensuring the interactivity of DSSs to make them more usable and widely applicable for a range of cases, and allowing for its modification to suit local needs. Reviewing a spectrum of optimization and decision making methods helped with the understanding of the characteristics of the decision problem that would warrant the use of any of these methods.

The second phase included a systems analysis to outline the technical, environmental, and socio-economic drivers, constraints, and parameters involved in selecting sustainable POU and POE drinking water treatment systems (Chapter 3). The systems analysis results outlined all the relevant information necessary for selecting a sustainable POU or POE system. The results of the analysis were used as the basis for developing the POU and POE systems knowledgebase and defining the characteristics and parameters that formulated the user input, the decision making rules, and the outcome of D4SPOUTS.

The third phase included incorporating the results of a systems analysis in a conceptual multi-criteria decision analysis (MCDA) framework for assessing the sustainability of POU and POE alternatives (Chapter 4). Sustainability assessment using multi-criteria decision analysis (MCDA): a multi-criteria model was developed to assess the sustainability of POU and POE devices. The model considers a number of sustainability objectives categorized under four main criteria groups (technical, economic, environmental, and sociocultural). A list of 20 indicators categorized under the four criteria groups was developed and the decision parameters were formulated into categorical or mathematical equations to calculate values for each indicator. The multi-criteria model employed the analytical hierarchy process (AHP) and a simple weighted sum of all indicators to calculate an aggregated value for a POU or POE system's sustainability.

The final phase included incorporating the conceptual MCDA framework in addition to other decision rules into an interactive computerized Decision Support System for Selecting Sustainable Point-of-Use and point-of-entry drinking water Treatment Systems (D4SPOUTS) and evaluating the success of D4SPOUTS in addressing the POU and POE selection problem (Chapter 5). The components of D4SPOUTS were built using Microsoft® Excel® and Visual Basic® for Applications. The quality of D4SPOUTS and aspects of its usability, applicability, and sensitivity analysis were demonstrated through a hypothetical case study for lead removal from drinking water.

A few challenges were faced throughout the development of D4SPOUTS:

1. Originally the plan was to consider not only POU or POE units but also combinations of these units that can form a treatment train. Lack of data and complications in developing combined treatment trains changed this plan to only include certified POU and POE devices as standalone treatment trains (whether they were individual technologies or groups of technologies with one certified device).

2. It was initially hoped that the data for developing the knowledgebase could come from NSF International and manufacturers, however, much of the devices' data were considered to be confidential and there was resistance from some manufacturers in making it available. This diverted our approach from trying to populate the full knowledgebase of certified POU and POE devices to developing a knowledgebase editor that can be used by manufacturers or other stakeholders to input new devices with full characterization. Only 10 devices were input in D4SPOUTS for the purpose of demonstration and sensitivity analysis.

3. Since the beginning of D4SPOUTS development it was decided that stakeholders' involvement should receive special attention. Substantial time and effort were invested in developing two questionnaires designed to capture stakeholders' thoughts on the developed hierarchy of indicators and their relative importance. The questionnaires were designed to

be interactive (e.g. indicators' definitions popped up when participants hovered over them) and informative. This proved to be worth the investment as the questionnaires' responses helped improve on the design of D4SPOUTS.

4. Since the number of devices in the knowledgebase will not exceed 6000 units (at least not in the near future), optimization methods were deemed unnecessary and multi-criteria decision analysis methods seemed like a better fit. The analytical hierarchy process (AHP) was used chosen for its ability to handle the decision problem in a structured manner.
5. The lack of data constrained the way indicators are calculated. Indicators that were expected to be quantifiable were occasionally assigned qualitative assessment methods instead. Moreover, this caused some indicators to lack of necessary variance to influence the selection process and as such they had to be removed from the list.
6. The plan was to increase the flexibility of D4SPOUTS by allowing a user to add one or more indicators to the indicators' hierarchy. However, due to the design of D4SPOUTS, the decision is based on three components; the user input of case characteristics, device characteristics in the knowledgebase, and decision logic. To be able to add a new indicator, major changes will have to be made to these three components. Thus the idea of having the possibility to automatically add a new indicator was abandoned.

This research project was more complex than expected. Since this is the first attempt to quantify the sustainability of POU and POE treatment devices, the challenges faced were numerous and difficult to overcome. The development of a decision support system is often a long term task that requires continuous update and enhancement. The best available and attainable knowledge was used in developing D4SPOUTS, it is envisioned that improvements on D4SPOUTS can be done as more knowledge of POU and POE devices become available.

6.1 Summary of Findings and Conclusions

A thorough investigation of the methods used to develop DSSs benchmarked a systematic approach to for this work (Chapter 2), from which we can make the following conclusions:

- The scope of the DSS, its intended use, and the elements considered are the main factors influencing the way a DSS is constructed. The application of a decision analysis method in the field of water treatment decision-making varies considerably.

- Technical considerations dominate the logic of previously developed treatment plant design DSSs. The systems analysis approach is yet to be appropriately exploited as the most comprehensive approach to problem analysis. Environmental issues coupled with social considerations have only recently been included in DSSs which set the benchmark for future DSSs.
- Joint consideration of the environmental, technical, economic, and sociocultural factors require the use of multiple criteria, which makes the decision process inherently multi-objective. This creates the need for assigning preference or importance weights to decision criteria or objectives.
- It is important to consider methods to decrease subjectivity of these weights through stakeholder involvement in the early stages of DSS development.
- A higher level of interactivity with the users should be the goal of future DSSs. Careful attention must be given to the various aspects of usability. User friendliness and usefulness of the DSS are the keys to the success or failure of a DSS.

Drawing upon the above investigation, a systems analysis was carried out for the sustainability of POU and POE treatment as a first step in developing the DSS (Chapter 3). From the analysis the following conclusions can be drawn:

- Existing standards, reports, and guidelines provide knowledge to assist with selecting and implementing POU/POE systems. Nevertheless, they require expert interpretation, whereas marketing techniques are designed to appeal to consumers regardless of their knowledge, and in some cases the actual need for a supplementary device.
- It is important to rely upon objective and professional resources when making an educated decision regarding which treatment system to use. This is a clear goal, especially in a marketing-intensive industry such as that of POU/POE devices, where advertising seems to dominate the decision-making process.
- There are concerns regarding the sustainability of POU and POE treatment, especially regarding administrative and logistical challenges. The process of developing the indicators helped to determine the important tenets of sustainability.

- The analysis helped develop 25 quantitative and qualitative indicators to promote the practical use of the concept of sustainability, and to compare and select among POU and POE systems. The indicators covered technical, economic, environmental, and socio-cultural aspects of implementing a POU or a POE system.
- Expert and stakeholder involvement is crucial for the verifying the relevance of the selection criteria and sustainability indicators. Such involvement helped ameliorate the developed indicators and refine them into 20 indicators.

Following the structuring of a selection framework and the definition of sustainability indicators, the Analytical Hierarchy Process (AHP), a recognized MCDA tool, was employed to construct the structural hierarchy of the indicators (Chapter 4). Pairwise comparison was used to help in the analysis of indicators' relative importance and develop the indicators' weights. The following conclusions were drawn from this exercise:

- Defining what the indicator is intended to measure is a start, however, the availability of data and parameters that can contribute to the value of the indicator required thorough investigation. Data availability can have a deleterious effect on the usability of the DSS.
- A balance is needed between the desire to encompass all aspects that pertain to sustainability in the selection process, and the practical challenges in calculating indicators to evaluate these aspects.
- Indicator manipulation is essential to help aggregate their values into a meaningful score. Aggregated scores are valued for their ability to integrate large amounts of information into one value that is useful for a general or comparative judgment. The indicators had to be normalized to range from 0-1 to allow for the aggregation of the indicators using a weighted sum method.
- The analytical hierarchy process is useful for structuring the selection problem, especially when the various elements of selection can be easily and logically outlined in a hierarchy. AHP allows for multi-level aggregation which enables in-depth analysis useful for developing sub-indices which can be used for decision reasoning.
- Continuous stakeholder involvement helps to reduce the subjectivity of MCDA methods. A survey was designed to develop the relative weights of the indicators based on the average

response of 19 stakeholders to a series of pairwise comparison questions pertaining to the relative importance of the sustainability indicators.

- Matrix algebra was used to check the consistency of the participants' responses and develop the weights based on the survey results. The use of the AHP weighted hierarchy in assessing the comparative sustainability of four POU and POE treatment alternatives was demonstrated.

The MCDA technique explained above was combined with designed screening rules, constraints, and case characteristics and applied to a knowledgebase of POU and POE treatment systems to develop D4SPOUTS (Chapter 5). The evaluation of D4SPOUTS showed that some of its main strengths include: (1) providing comprehensive decision analysis and support structured in systematic way, (2) the interface is interactive allowing the user to input cases, devices, and even influence the decision logic, and (3) the output allows the user to thoroughly explore the shortlisted alternatives and gain a better understanding of the decision reasoning.

6.2 Future Directions and Implications for the Water Community

In the market-based POU and POE treatment industry, D4SPOUTS is envisioned to help make an informed decision based on sustainability analysis of alternatives POU and POE devices. The continuous enhancement of D4SPOUTS can also help convince manufacturers to target improvement of POU and POE devices' sustainability in their product development strategies. For example, D4SPOUTS could be adopted by an arm's length association or organization to fully populate it with information and advertise it as a useful tool for selecting sustainable devices. Table 6.1 outlines some of the main implications of D4SPOUTS to the various stakeholders in POU and POE treatment.

Indicators and screening rules can be further enhanced when more data is available to account for water quality and treatment device performance variability. It is also envisioned that after populating D4SPOUTS with a substantial list of POU and POE devices, a more rigorous validation process can be implemented. A suggestion for a better sensitivity analysis of D4SPOUTS outcome is to use the weights assigned by each expert to represent the view of a particular group of stakeholders (such as: manufacturers, certifying agencies, researchers, etc…) and compare the outcome to that resulting from averaging the weights resulting from all the experts. Furthermore, the availability of devices' and components' characterization should help in the consideration of combinations of devices and/or components as potential solutions. This can be coded using an alternative generation algorithm whereby the number of potential solutions increases exponentially. To this end D4SPOUTS will need to incorporate other optimization methods to help deal with the increased number of alternatives.

The future of DSSs in water and wastewater treatment should focus more on integrating various data within the context of a system view of water resources management. This integration will have implications on knowledge representation and reasoning practice. As more data of sustainability parameters become available for use in D4SPOUTS, more methods or combinations of methods should be derived to incorporate the new data in the selection process. Also, data uncertainties and reliability can be included by adopting a probabilistic or fuzzy logic knowledge representation approaches to increase the validity and credibility of the D4SPOUTS output.

Table 6.1 Implications of D4SPOUTS to POU and POE Stakeholders

Stakeholder	**Implication of D4SPOUTS**
Government monitoring agency	D4SPOUTS ensures that the selected POU or POE devices will comply with regulations. This may also encourage the expansion of the scope of acceptance of POU or POE systems in complying with regulations.
Water purveyor	Installed systems meet customer satisfaction goals, regulatory requirements and ensure technical and economic sustainability.
POU and POE systems supplier/manufacturer associations	D4SPOUTS can encourage manufacturers to strive to enhance the sustainability of their devices to increase their ranking on the shortlisted devices. This can also increase consumer confidence in their products and their market share.
Independent certification organization	By adopting D4SPOUTS, an organization such as NSF International can provide better services to consumers in their search for sustainable POU and POE devices.
Water associations	D4SPOUTS can be used as a tool to increase consumer awareness with regard to POU and POE treatment. It can also help in outlining areas of research to increase the sustainability of POU and POE devices.
Consumers and consumer organizations	D4SPOUTS addresses many of the concerns and confusion consumers have about POU and POE devices. It can be tailored to be used as a consumer aid tool.

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Appendix A

Questionnaire 1: Expert's Assessment of the Developed POU/POE Sustainability Indicators

Sample questionnaire response

Questionnaire to assess the effectiveness of developed POU/POE sustainability criteria and indicators

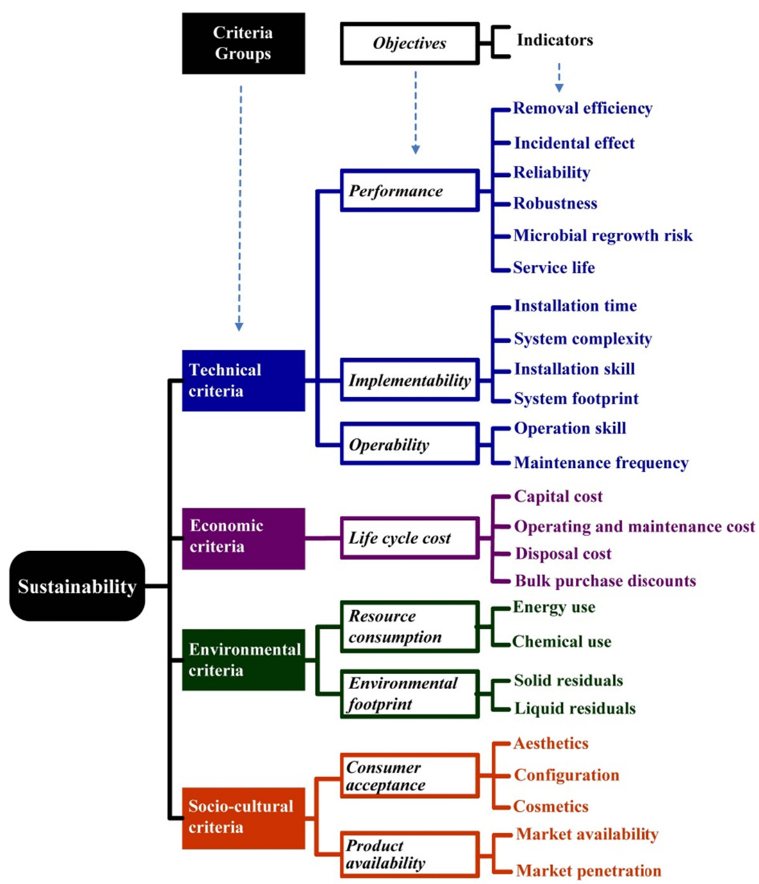
Name:

Affiliation: NSF International

Email:

Date: 17-Nov-09
dd mmm yy

This questionnaire asks for your expert opinion on:
(1) the importance of the provided indicators with regard to the selection of a sustainable point-of-use or point-of-entry (POU/POE) drinking water treatment train; and
(2) the effectiveness with which these indicators are measured.



1

1) What's your opinion on the indicators used to assess **"PERFORMANCE"?**

Indicator	**Description**	← →	**Comments**
Removal efficiency	Reduction efficiency (%) of treatment train for target contaminant (chemical and microbial) as certified by NSF international	● ○ ○ ○ ○	In my opinion, this is the most important performance criterion.
Incidental effect (IE)	Additional removal of contaminants other than those targeted in the influent water, IE = $(C_t - C_w)/C_t$ (range 0 to 1) C_t : # contaminants removed by the train (as certified by NSF) (e.g. = 5) C_w : # target contaminants in influent water (e.g. = 3) e.g. IE = (5-3)/5 = 0.4	○ ○ ● ○ ○	
Reliability	Sensitivity to malfunctioning Reliability = (Pt – 1)/Pt Pt : # individual processes in train removing target contaminant e.g. a train having GAC and RO used to remove arsenic will have Reliability = (2-1)/2 = 0.5	○ ● ○ ○ ○	
Robustness	A qualitative assessment of sensitivity of a treatment train concerning toxic contaminants, shock loads, and seasonal effects (rating of low, moderate, or high robustness)	○ ○ ○ ● ○	Seasonal effects are difficult to predict and affect different consumers differently.
Microbial regrowth risk	An indication of the potential for increased heterotrophic bacteria (HPC), and the existence of a mitigation technique (rating of low moderate and high risk)	○ ○ ○ ○ ●	WHO concluded that heterotrophic bacteria are a very low risk for non-sensitive populations.
Service life	Estimated service life until retirement in liters	○ ○ ○ ○ ●	There is a balance between cost and capacity because of size of filter, so these effects offset / correct.

Please write any additional comments here

2) What’s your opinion on the indicators used to assess **“IMPLEMENTABILITY”?**

Indicator	**Description**	← →	**Comments**
Installation skill	A qualitative assessment of the level of skill required to install the train Low – installed by homeowner Moderate–unit distributer is required High – professional plumber/ electrician required	○ ● ○ ○ ○	I think this is an important consideration.
Installation time	Average time to install the train (hours)	○ ○ ○ ○ ●	Over the life of the treatment system, hopefully the initial installation time will be a non-issue
System complexity	A qualitative assessment of the complexity of a treatment train that considers the number of processes and accessories (rating of low, moderate, or high complexity)	○ ○ ○ ○ ●	This seems to be addressed through other criteria under performance and doesn't seem to be as relevant here.
System footprint	Indication of average volume (or area) occupied by the train (m^2 or m^3)	○ ● ○ ○ ○	This is a real consideration and limitation of systems.

3) What’s your opinion on the indicators used to assess **“OPERABILITY”?**

Indicator	**Description**	← →	**Comments**
Operation skill	A qualitative assessment of the level of skill required to operate the treatment train. Low – No formal training required Moderate – Training is useful High – Operator training required	● ○ ○ ○ ○	Some systems require considerable understanding, and lack of understanding can mean ineffective treatment.
Maintenance frequency	Indication of frequency of maintenance required, expressed by: No. of maintenance hours / year + No. components to change / year	○ ● ○ ○ ○	This is also a real consideration for busy consumers.

4) What's your opinion on the indicators used to assess **"LIFE CYCLE COST"?**

Indicator	**Description**	← →	**Comments**
Capital cost	A qualitative assessment of the cost of purchase and installation (rating of low, moderate, or high)	○ ○ ○ ● ○	This requires consideration, but is much less important than O&M costs.
Operating and maintenance cost	A qualitative assessment of the operating and maintenance cost (rating of low, moderate, or high)	● ○ ○ ○ ○	Very important.
Disposal cost	A qualitative assessment of the residuals disposal and decommissioning costs (rating of low, moderate, or high)	○ ○ ○ ○ ●	
Bulk purchase discount	A qualitative assessment of the potential discount on train bulk purchase (rating of low, moderate, or high)	○ ○ ○ ● ○	

Please write any additional comments here

5) What's your opinion on the indicators used to assess **"RESOURCE CONSUMPTION"?**

Indicator	Description	← →	Comments
Energy use	Energy used by train per unit of treated water kWh/liter	○ ○ ○ ● ○	I see this as part of O&M, not necessarily relevant as its own consideration.
Chemical use	A qualitative assessment of chemicals used by train per unit of treated water. **Low**: chemicals used are of small quantity and mild or no impact **Moderate**: chemicals used are of larger quantity or of higher impact **High**: chemicals used are of larger quantity or of higher impact	○ ● ○ ○ ○	This is important because it reflects cost, maintenance, and possibly safety issues.

6) What's your opinion on the indicators used to assess **"ENVIRONMENTAL FOOTPRINT"?**

Indicator	Description	← →	Comments
Solid residuals	A qualitative assessment of the treatment train production of solid waste per unit of treated water. **Low**: residuals can be disposed of in a standard solid waste management system, or the manufacturer provides a residuals collection system **Moderate**: residuals can be disposed of for a small cost **High**: residuals are hazardous and need special and costly treatment	○ ● ○ ○ ○	I don't think too many systems have solid residuals, but if they are present, they require consideration.
Liquid residuals	A qualitative assessment of the treatment train production of liquid waste per unit of treated water, Rating is similar to that of solid residuals	○ ○ ● ○ ○	This issue is much more a consideration where water is scarce, and less a consideration in regions

Please write any additional comments here

7) What's your opinion on the indicators used to assess **"CONSUMER ACCEPTANCE"?**

Indicator	Description	← →	Comments
Aesthetics	An indication of the aesthetic water quality produced by the system, including issues such as warm or low pressure water (rating of low, moderate, or high aesthetic quality)	● ○ ○ ○ ○	Research has shown that aesthetics are the most important driver of treatment system purchases.
Configuration	A rating of satisfaction with the system configuration: Under the sink, countertop, pitcher, etc. (rating of low, moderate, or high satisfaction)	● ○ ○ ○ ○	This is also very important given the focus consumers place on the appearance of kitchens.
Cosmetics	An indication of the attractiveness and communication of the system with the user: 1. Decorative shape and color 2. Transparent vs. solid casing 3. Performance information display (rating of low, moderate, or high attractiveness)	● ○ ○ ○ ○	

8) What's your opinion on the indicators used to assess **"PRODUCT AVAILABILITY"?**

Indicator	Description	← →	Comments
Market availability	A qualitative assessment of the market availability of a unit indicated by the coverage of the chain of stores it is sold at (e.g. units sold at Canadian Tire vs. units sold at Home Depot or Sears, or units sold online etc.)	○ ○ ○ ● ○	I don't see this as a big issue unless the product is very difficult to locate or obtain.
Market penetration	A quantitative assessment of the treatment train availability in the market expressed by the number of NSF certified units that fit the treatment train (e.g. # of certified units that fit the train prefilter-GAC-RO-UV)	○ ○ ○ ● ○	

6

Thank You

Summary of questionnaire participants and response

1. **W,** University of Waterloo
2. **E**, Conestoga-Rovers & Associates
3. **R1**, NSF International
4. **Y**, Water Quality Association
5. **J1,** Underwriters Laboratory
6. **K,** XCG Consultants
7. **T,** Indian and Northern Affairs Canada
8. **J2,** City of Toronto
9. **R2,** Wilfred Laurier University
10. **F1,** Canadian Standards Association International
11. **F2,** Health Canada

1) What's your opinion on the indicators used to assess **"PERFORMANCE"?**

Indicator	←			→		**Comments**
Removal efficiency	10			1		
Incidental effect	1	3	4	2	1	• Rank low: assuming that the customer actually understands what needs to be removed **J2**
Reliability	5	4	2			• Rank high: Multibarrier approach **E** • Rank high: Depends on whether using POE owned & maintained by municipality or POU owned & maintained by customer **J2** • Rank Average: Not sure if a single RO treatment train should get a reliability of 0 **F1**
Robustness	2	4	3	2		• Rank average: I'm assuming health effects based on long-term consumption **J2** • Rank low: Seasonal effects are difficult to predict and affect different consumers differently **R1** • Rank Average: would have to provide criteria with the device **F2**
Microbial regrowth risk	2	3	2	3	1	• Rank high: should consider how this can be defined, may be difficult but it is an important criteria **R2** • Rank high: Conditional importance **W** • Rank low: As long as regrowth is HPC, and not "repair" of pathogens, not a significant concern **E** • Rank low: WHO concluded that heterotrophic bacteria are a very low risk for non-sensitive populations **R1** • Rank Average: not a health indicator **F2**
Service life	5	2	3		1	• Rank average: better in economic indicators **W** • Rank low: There is a balance between cost and capacity because of size of filter, so these effects offset / correct **R1**

J2: It may be important to differentiate between POE units which may be owned and maintained by municipal systems (as per O.Reg. 170, Schedule 3) POE or POU units that may be required for regulated "small systems" (under O. Reg. 319) and those designed for general public use.

2) What’s your opinion on the indicators used to assess **“IMPLEMENTABILITY”?**

Indicator	←			→		**Comments**
Installation skill	5	3	2	1		
Installation time	1	3	3	2	2	• Rank average: Once a skill level has been determined installation becomes relatively unimportant unless homeowner installs **W** • Rank low: Over the life of the treatment system, hopefully the initial installation time will be a non-issue **R1** • Rank low: this is dependent on the previous one, if this is not "low", installed by the homeowner, then likely wouldn't be as influential in its consumer appeal **R2**
System complexity	1	4	4	1	1	• Rank high: System complexity would not be independent from installation skill, duration, or footprint **E** • Rank average: Depends on the challenge(s) being faced **J2** • Rank low: This seems to be addressed through other criteria under performance and isn't as relevant here **R1** • Rank high: There needs to be a distinction between the complexity of the treatment train relative to the complexity of operation. You don't want people to avoid it if it can be operated easily despite complexity of the system **F2**
System footprint	2	5	4			• Rank high: a real consideration and limitation of systems **R1** • Rank average: Important but probably largely irrelevant (for most POU treatment trains anyway)-POE different story **W** • Rank average: Depends very much on whether POE or POU. The smaller the better in general **J2**

3) What’s your opinion on the indicators used to assess **“OPERABILITY”?**

Indicator	←			→		**Comments**
Operation skill	6	4			1	• Rank high: Some systems require considerable understanding, and lack of understanding can mean ineffective treatment **R1** • Rank high: this one will be of high importance re: general acceptance **R2**
Maintenance frequency	3	5	1		2	• Rank high: This is also a real consideration for busy consumers **R1** • Rank average: Operational skill, maintenance frequency are also coupled **E** • Rank high: Should be more frequent than hours per year. People may just assume they can leave for the year. Would have weekly or monthly as metric **F2**

4) What's your opinion on the indicators used to assess **"LIFE CYCLE COST"?**

Indicator	←				→	**Comments**
Capital cost	4	5	1	1		• Rank low: This requires consideration, but is much less important than O&M costs **R1** • Rank average: This is a difficult assessment. What is low cost to some is considered prohibitive by others. Attach dollar figures? Not sure.... **F2**
O&M cost	3	6	2			• Rank high: very important **R1**
Disposal cost	1	5	1	2	2	• Rank low: Generally considered to be part of O&M costs **E** • Rank low: Not sure that this is relevant for the type of devices being considered here. This could be confusing to the consumer. **F2**
Bulk purchase discount		3	4	3	1	• Rank high: Rather high for POE (especially if owned by municipality) **J2** • Rank low: Discount isn't important unless you're installing a relatively large number of similar systems **E** • Rank avg. to low: This could be confusing to the consumer. Would have to distinguish this group from small systems **F2**

5) What's your opinion on the indicators used to assess **"RESOURCE CONSUMPTION"?**

Indicator	←				→	**Comments**
Energy use	4	5	1	1		• Rank average: Somewhat dependent on location - local energy source and costs **E** • Rank low: I see this as part of O&M, not necessarily relevant as its own consideration **R1**
Chemical use	4	3	4			• Rank high: Considering more than just cost, also operator effort, health & safety **E** • Rank high: This is important because it reflects cost, maintenance, and possibly safety issues **R1** • Rank average: This could be confusing to the consumer. Would have to distinguish this group from small systems **F2**

6) What's your opinion on the indicators used to assess **"ENVIRONMENTAL FOOTPRINT"?**

Indicator	←				→	**Comments**
Solid residuals	4	4	1	1	1	• Rank high: I don't think too many systems have solid residuals, but if they are present, they require consideration **R1** • Rank high: more universal in application than the previous indicators **F2**
Liquid residuals	3	4	1	3		• Rank average: This issue is much more a consideration where water is scarce, and less a consideration in regions **R1** • Rank high: Not sure that this is a good indicator. Is this sludge? If not, provide an example. Should consider the quantity of water wasted (reject water) as an indicator **F2**

7) What’s your opinion on the indicators used to assess **“CONSUMER ACCEPTANCE”?**

Indicator	←				→	**Comments**
Aesthetics	6	2	2		1	• Rank high: Research has shown that aesthetics are the most important driver of treatment system purchases **R1** • Rank average: I would rank higher but I don't know if consumers would have any awareness of these issues prior to purchase **W** • Rank low: Not sure I want to encourage the use of an indicator that could be misinterpreted as taste-related. Low pressure and warm water is performance, not aesthetic **F2**
Configuration	2	8	1			• Rank high: High for POU **J2** • Rank high: This is also very important given the focus consumers place on the appearance of kitchens **R1** • Rank average: Again I'm not sure if consumers have a preconceived notion or understand the differences **W**
Cosmetics	4	2	4	1		• Rank high: High for POU **J2** • Rank high: More important to consumers but should be important to municipal suppliers if they want public buy-in (acceptance) **W** • Rank low: Monitoring equipment that displays performance data should be considered in terms of ease of operation, not aesthetic appearance **E**

8) What’s your opinion on the indicators used to assess **“PRODUCT AVAILABILITY”?**

Indicator	←				→	**Comments**
Market availability	2	4	2	1	2	• Rank low: I don't see this as a big issue unless the product is very difficult to locate or obtain **R1** • No rank: marketing is part of the problem rather than the solution as it now stands **J2** • Rank low: Unless you are grouping by type, this would be horribly difficult to undertake. Manufacturers have a different model for different clients (HD vs CT) and even produce the same device under different brand labels!! **F2**
Market penetration	4	4	1	1	1	• No rank: marketing is part of the problem rather than the solution as it now stands **J2**

Appendix B

Questionnaire 2: Stakeholders' Opinion on the Relative Importance of POU/POE Sustainability Indicators

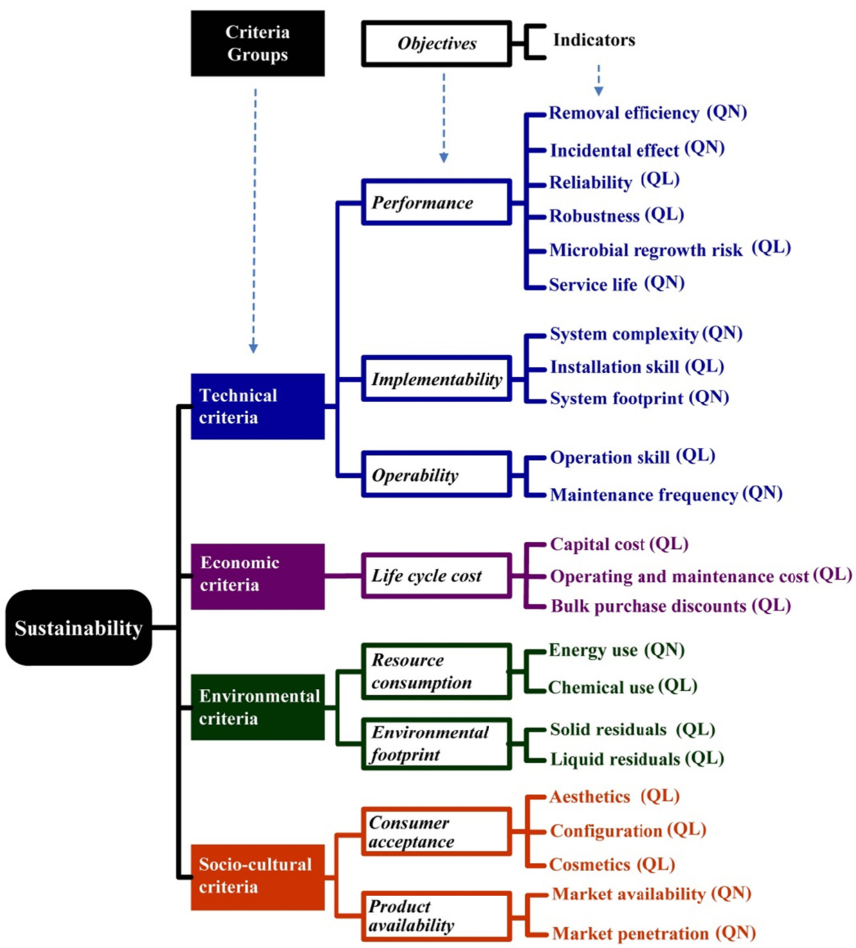
Sample questionnaire response

Name:

Affiliation: CSA International

Email: **Date:** 29-Mar-10
dd mmm yy

This questionnaire is designed to solicit your opinion on the relative importance of a system of indicators with regard to the selection of the best point-of-use or point-of-entry (POU/POE) drinking water treatment train from among hundreds of POU/POE alternatives to treat water of a particular quality. Below is the hierarchy of indicators to be used, and a detailed description of each indicator will appear when you hover over it.



1

Here is an Example on how to answer this questionnaire

	Extreme	V. Strong	Strong	Moderate	Equal	Moderate	Strong	V. Strong	Extreme		
Performance										**Implementability**	Performance is very strongly more important than Implementability
Performance										**Operability**	Performance is moderately to strongly more important than Operability
Implementability										**Operability**	Implementability is equally important as Operability

Please tick the box indicating which criteria is more important to sustainability

Technical	Economic
Technical	Environmental
Technical	Sociocultural
Economic	Environmental
Economic	Sociocultural
Environmental	Sociocultural

Please tick the box indicating which TECHNICAL objective is more important

Performance	Implementability
Performance	Operability
Implementability	Operability

Please tick the box indicating which ENVIRONMENTAL objective is more important

Resource consumption	Environmental footprint

Please tick the box indicating which SOCIOCULTURAL objective is more important

Consumer acceptance	Product availability

Remember to hover over an indicator to see its description

Please tick the box indicating which **PERFOMANCE** criterion is more important

	Extreme		V. Strong		Strong		Moderate		Equal		Moderate		Strong		V. Strong		Extreme	
Removal efficiency			■															Incidental effect
Removal efficiency					■													Reliability
Removal efficiency							■											Robustness
Removal efficiency									■									Microbial regrowth risk
Removal efficiency									■									Service life
Incidental effect															■			Reliability
Incidental effect													■					Robustness
Incidental effect											■							Microbial regrowth risk
Incidental effect															■			Service life
Reliability								■										Robustness
Reliability											■							Microbial regrowth risk
Reliability											■							Service life
Robustness									■									Microbial regrowth risk
Robustness													■					Service life
Microbial regrowth risk													■					Service life

Please tick the box indicating which **IMPLEMENTABILITY** criterion is more important

	Extreme		V. Strong		Strong		Moderate		Equal		Moderate		Strong		V. Strong		Extreme	
System complexity													■					Installation skill
System complexity							■											System footprint
Installation skill							■											System footprint

3

Remember to hover
over an indicator to
see its description

Please tick the box indicating which OPERABILITY criterion is more important

	Extreme	V. Strong	Strong	Moderate	Equal	Moderate	Strong	V. Strong	Extreme	
Operation skill	☐	☐	■	☐	☐	☐	☐	☐	☐	Maintenance frequency

Please tick the box indicating which ECONOMIC criterion is more important

	Extreme	V. Strong	Strong	Moderate	Equal	Moderate	Strong	V. Strong	Extreme	
Capital cost	☐	☐	☐	☐	☐	☐	■	☐	☐	O & M cost
Capital cost	☐	☐	☐	■	☐	☐	☐	☐	☐	Bulk purchase discount
O & M cost	☐	☐	■	☐	☐	☐	☐	☐	☐	Bulk purchase discount

Please tick the box indicating which RESOURCE CONSUMPTION criterion is more important

	Extreme	V. Strong	Strong	Moderate	Equal	Moderate	Strong	V. Strong	Extreme	
Energy use	☐	☐	☐	☐	☐	☐	■	☐	☐	Chemicals use

Please tick the box indicating which ENVIRONMENTAL FOOTPRINT criterion is more important

	Extreme	V. Strong	Strong	Moderate	Equal	Moderate	Strong	V. Strong	Extreme	
Solid residuals	☐	☐	☐	☐	☐	☐	■	☐	☐	Liquid residuals

Please tick the box indicating which consumer acceptance criterion is more important

	Extreme	V. Strong	Strong	Moderate	Equal	Moderate	Strong	V. Strong	Extreme	
Aesthetics	☐	■	☐	☐	☐	☐	☐	☐	☐	Configuration
Aesthetics	☐	☐	■	☐	☐	☐	☐	☐	☐	Cosmetics
Configuration	☐	☐	☐	☐	☐	■	☐	☐	☐	Cosmetics

Please tick the box indicating which product availability criterion is more important

	Extreme	V. Strong	Strong	Moderate	Equal	Moderate	Strong	V. Strong	Extreme	
Market availability	☐	■	☐	☐	☐	☐	☐	☐	☐	Market penetration

Thank you

4

Appendix C

Info-sheets for 20 Sustainability Indicators

<table>
<tr><td>Criteria Group</td><td>Technical</td><td>Objective</td><td>Maximize Performance</td></tr>
<tr><td>Indicator of</td><td colspan="3">Incidental Effect</td></tr>
<tr><td>Description</td><td colspan="3">A quantitative assessment of the treatment device’s ability to remove additional contaminants other than those specifically targeted in the influent water</td></tr>
<tr><td>Evaluation</td><td colspan="3">The rescaling equation for calculating the indicator is
Incidental Effect $IE = \dfrac{CR - CR_{\min}}{CR_{\max} - CR_{\min}}$
CR : number of contaminants removed by the treatment device (as certified to NSF/ANSI standards)
CR_{max} : Highest number of contaminants removed by a treatment device
CR_{min} : Lowest number of contaminants removed by a treatment device</td></tr>
<tr><td>Example</td><td colspan="3"><table>
<tr><th>Device</th><th>CR</th><th>IE</th></tr>
<tr><td>eSpring Model 100185 (100189</td><td>37</td><td>1</td></tr>
<tr><td>GE PNRQ15FBL</td><td>14</td><td>0.36</td></tr>
<tr><td>GE GNSV70RBL</td><td>12</td><td>0.31</td></tr>
<tr><td>eSpring Model 100185 (100188)</td><td>37</td><td>1</td></tr>
<tr><td>CR_{max}</td><td>37</td><td></td></tr>
<tr><td>CR_{min}</td><td>1</td><td></td></tr>
</table></td></tr>
<tr><td>Comments</td><td colspan="3">Devices are sometimes certified for removal of the same target contaminant under different standards. To avoid double counting, the claim for a contaminant’s removal was only counted once, even if a device is certified to remove it under more than one standard.</td></tr>
</table>

Criteria Group	**Technical**	**Objective**	**Maximize Performance**
Indicator of	**Reliability**		
Description	A quantitative assessment of the sensitivity to malfunctioning by measuring redundancy in the treatment device.		
Evaluation	The rescaling equation used to evaluate reliability Reliability $RL = \frac{P - P_{\min}}{P_{\max} - P_{\min}}$ P : redundant processes in the treatment device used to remove a target contaminant (= number of processes removing that contaminant – 1) P_{max}: Highest number of redundant processes in a device used to remove a target contaminant P_{max}: Lowest number of redundant processes in a device used to remove a target contaminant The indicator is evaluated for a number of important contaminants, these are: lead, arsenic, chromium (hexavalent), cysts, fluoride, MTBE, nitrite/nitrate, radon, perchlorate, and VOC contaminant category. If there are no target contaminants identified in the case or if the target contaminant is not one of the important contaminants, then all the devices are rated equally for reliability and are given a value of 1. If there is only one target contaminant identified, then the reliability of a device is that calculated for that target contaminant. If there is more than one target contaminant identified which belong to the group of main contaminants, then the reliability of a device is the lowest reliability of those calculated for each target contaminant.		
Example	Evaluating reliability when Lead is the target contaminant		

Device	Lead P	RL
eSpring Model 100185 (100189)	0	0
GE PNRQ15FBL	2	1
GE GNSV70RBL	1	0.5
eSpring Model 100185 (100188)	0	0
Max	2	
Min	0	

Criteria Group	**Technical**	**Objective**	**Maximize Performance**
Indicator of	**Robustness**		
Description	A qualitative assessment of the sensitivity of a treatment device concerning shock loads, and seasonal effects		

Evaluation

Robustness is influenced by two factors

1) Risk of shock loads emanating from source water type (SR)

Source	Categorical Risk Rating (SR)
Shallow Ground Water	Moderate (0.5)
Deep Ground Water	Low (0.75)
Surface Water	High (0.25)
Rain Water	High (0.25)
Centrally Treated Water	Low (0.75)

2) The level of sophistication of the device's failure and filter replacement warning mechanism as an indication of the responsiveness to failure due to shock loads or seasonal effects. Two aspects are considered:

Product control
– Shutdown: termination of the discharge of treated water; or
– Low-flow: reduction by 50-75% of the clean system flow rate.

Failure alarm
– Audible: an alarm connected to an acceptable power source; or
– Visual: flashing light connected to an acceptable power source.

Product control (PC)	Failure alarm (FA)	WM
Shutdown (1) Low-flow (0.5) None (0)	Audible (0.75) Visual (0.5) Both (1) None (0)	= PC + FA – PC x FA

The mutual equivalence equation used to calculate the indicator of robustness (RB) is: $RB = SR + WM - SR \times WM$

If one of the ratings is maximum (e.g. SR or WM = 1), then the result is always RB = 1; however, for SR and WM < 1; ratings work synergistically; for example, when SR = 0.25 and WM = 0.5 result is RB = 0.625

Example

Evaluating robustness when the source is centrally treated water

Device Model	SR	PC	FA	WM	RB
eSpring Model 100185 (100189)	0.75	0.5	0.75	0.875	0.969
GE PNRQ15FBL	0.75	1	0.5	1	1
GE GNSV70RBL	0.75	0.5	0.5	0.75	0.938
eSpring Model 100185 (100188)	0.75	0.5	0.75	0.875	0.969

Criteria Group	Technical	Objective	Maximize Performance
Indicator of	Microbial Regrowth Risk		
Description	A qualitative assessment of the potential for growth of heterotrophic bacteria (HPC), and the existence of a mitigating technique in the treatment device		
Evaluation	There are two parameters used in calculating the indicator 3. Regrowth risk (RR): typically it depends on the processes in the treatment device and the quality of the source water. However, since the quality of the source water for a particular case is fixed then the only parameter considered here is the type of processes used in the treatment device. a. Low risk: membranes, ion exchange (regenerated), and solid block activated carbon; b. Moderate risk: silver or copper impregnated solid block activated carbon or ion exchange (not regenerated); c. High risk: granular activated carbon, sediment filters, or particulate prefilters. 4. Mitigation technique (MT): a parameter indicating whether or not a mitigation technique follows treatment units which may facilitate biofilm growth. Such techniques include: UV or membrane processes at the end of the treatment train, or ion exchange regeneration process in softeners. Categorical rating of the indicator of Microbial Regrowth Risk (MRR) None: no regrowth risk (e.g. single UV units) (1) Low: Low or moderate regrowth risk + mitigation (0.75) Moderate: Low regrowth risk + no mitigation (0.5) Or High regrowth risk + mitigation (0.5) High: Moderate regrowth risk + no mitigation (0.25) Very High: High regrowth risk + no mitigation (zero)		
Example	see below		

Device	Treatment Train	RR	MT	MRR
eSpring Model 100185 (100189)	PPF-PPF-SBAC-UVB	Low	Y	0.75
GE PNRQ15FBL	SBAC-RO-SBAC	Low	N	0.5
GE GNSV70RBL	SBAC-SBAC	Low	N	0.5
eSpring Model 100185 (100188)	PPF-PPF-SBAC-UVB	Low	Y	0.75

PPF = Particulate pre-filter, SBAC = Solid Block Activated Carbon

UVB = Ultraviolet disinfection class B, RO = Reverse Osmosis

<table>
<tr><td>Criteria Group</td><td>Technical</td><td>Objective</td><td colspan="2">Maximize Implementability</td></tr>
<tr><td>Indicator of</td><td colspan="4">Installation Skill</td></tr>
<tr><td>Description</td><td colspan="4">A qualitative assessment of the level of skill required to install the treatment device</td></tr>
<tr><td>Evaluation</td><td colspan="4">Categorical rating of the indicator of Installation Skill (IS) is based on the ease of installing the device
None: no installation required (1)
Low: installation required by homeowner (0.75)
Moderate: installation required by distributer (0.5)
High: installation required by plumber or electrician (0.25)
Very High: professional plumber and electrician are required (zero)</td></tr>
<tr><td rowspan="6">Example</td><td>Device</td><td>Treatment Train</td><td>Configuration</td><td>IS</td></tr>
<tr><td>eSpring Model 100185 (100189)</td><td>PPF-PPF-SBAC-UVB</td><td>Counter top conn. faucet</td><td>0.75</td></tr>
<tr><td>GE PNRQ15FBL</td><td>SBAC-RO-SBAC</td><td>Plumbed in to separate tap</td><td>0.5</td></tr>
<tr><td>GE GNSV70RBL</td><td>SBAC-SBAC</td><td>Plumbed in to separate tap</td><td>0.5</td></tr>
<tr><td>eSpring Model 100185 (100188)</td><td>PPF-PPF-SBAC-UVB</td><td>Plumbed in to separate tap</td><td>0.5</td></tr>
<tr><td colspan="4">PPF = Particulate pre-filter, SBAC = Solid Block Activated Carbon
UVB = Ultraviolet disinfection class B, RO = Reverse Osmosis</td></tr>
</table>

Criteria Group	Technical	Objective	Maximize Implementability
Indicator of	**System Footprint**		
Description	A quantitative assessment of the volume and area occupied by the treatment device.		
Evaluation	The rescaling and weighted sum equation for calculating the indicator of system footprint (SF) is System Footprint $SF = \frac{1}{2}\frac{V_{max} - V}{V_{max} - V_{min}} + \frac{1}{2}\frac{A_{max} - A}{A_{max} - A_{min}}$ V : volume of device (cm^3) V_{max} : highest volume of a device (cm^3) V_{min} : lowest volume of a device (cm^3) A : area of device (cm^2) A_{max} : highest area of a device (cm^2) A_{min} : lowest area of a device (cm^2)		
Example	(see table below)		
Comments	When calculating the system footprint for an RO unit the storage tank was included.		

Device	V (cm^3)	A (cm^2)	SF
eSpring Model 100185 (100189)	10,360.668	316.84	0.83
GE PNRQ15FBL (RO)	31,024.102	888.092	0
GE GNSV70RBL	5,936.300	204.7	1
eSpring Model 100185 (100188)	10,360.668	316.84	0.83
Max	31,024.102	888.092	
Min	5,936.300	204.7	

Criteria Group	Technical	Objective	Maximize Operability
Indicator of	Operation and Maintenance Skill		
Description	A qualitative assessment of the level of skill required to operate and maintain the treatment device.		

Evaluation

Two parameters are considered in the indicator calculation

3. Level of difficulty for changing the device's components
4. Level of sophistication of the cleaning operations

The weighted sum equation used to calculate the indicator:

Operation and Maintenance Skill $OS = \frac{1}{2}DC + \frac{1}{2}CL$

DC : a categorical rating of the difficulty of change for the device's components

None: very easy to change (no tools required) (1)

Low: requires basic tools, or step by step guidelines to change (0.75)

Moderate: requires basic tools and step by step guidelines (0.5)

High: require sophisticated tools and step by step guidelines (0.25)

Very High: require sophisticated tools, step by step guidelines, and involves electrical work (zero)

CL : a categorical rating of the sophistication of the cleaning operation

None: no cleaning (1)

Low: occasional rinsing (0.75)

Moderate: scrubbing and rinsing (0.5)

High: chemical rinse (0.25)

Very High: scrubbing and chemical rinse (zero)

Example

Device	Mechanism of change	EC	Cleaning Operation	CL	OS
eSpring Model 100185 (100189)	Unplug, Unscrew, & Replace	0.25	None	1	0.625
GE PNRQ15FBL	Twist & Lock	0.75	None	1	0.875
GE GNSV70RBL	Twist & Lock	0.75	None	1	0.875
eSpring Model 100185 (100188)	Unplug, Unscrew, & Replace	0.25	None	1	0.625

<table>
<tr><td>Criteria Group</td><td>Technical</td><td>Objective</td><td>Maximize Operability</td></tr>
<tr><td>Indicator of</td><td colspan="3">Maintenance Frequency</td></tr>
<tr><td>Description</td><td colspan="3">A quantitative assessment of the frequency of maintenance required for the treatment device</td></tr>
<tr><td>Evaluation</td><td colspan="3">Two parameters are considered in the indicator calculation
1) Service life until maintenance in liters of filtered water
2) Number of components that need to be changed (not processes, i.e. there are systems that require that you change a component that covers a number of processes)
The rescaling and weighted sum equation used to calculate the indicator:
Maintenance Frequency $MF = \frac{3}{4}\frac{SL - SL_{\min}}{SL_{\max} - SL_{\min}} + \frac{1}{4}\frac{CO_{\max} - CO}{CO_{\max} - CO_{\min}}$
SL : service life of device (liters)
SL_{max} : Highest service life of a device
SL_{min} : Lowest service life of a device
CO : number of components to change
CO_{max} : Highest number of components to change for a device
CO_{min} : Lowest number of components to change for a device</td></tr>
<tr><td>Example</td><td colspan="3">
<table>
<tr><th>Device</th><th>SL</th><th>CO</th><th>Norm SL</th><th>Norm CO</th><th>MF</th></tr>
<tr><td>eSpring Model 100185 (100189)</td><td>5000</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>GE PNRQ15FBL</td><td>3400</td><td>3</td><td>0.636</td><td>0</td><td>0.478</td></tr>
<tr><td>GE GNSV70RBL</td><td>600</td><td>2</td><td>0</td><td>0.5</td><td>0.125</td></tr>
<tr><td>eSpring Model 100185 (100188)</td><td>5000</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>Max</td><td>5000</td><td>3</td><td></td><td></td><td></td></tr>
<tr><td>Min</td><td>600</td><td>1</td><td></td><td></td><td></td></tr>
</table>
</td></tr>
</table>

Criteria Group	**Economic**	**Objective**	**Minimize Life Cycle Cost**
Indicator of	**Capital Cost**		
Description	A quasi-quantitative assessment of the cost of purchase and installation of the treatment device		
Evaluation	There are two parameters used to calculate the indicator 1) The estimated purchase cost of a treatment device normalized against the max and min purchase cost of treatment devices 2) The rating of installation cost which is directly proportional to the level of installation skill required The rescaling and weighted sum equation used to calculate the indicator: Capital Cost $CC = \frac{2}{3}\frac{PC_{max} - PC}{PC_{max} - PC_{min}} + \frac{1}{3}IC$ PC : Purchase cost is estimated in CAD based on sales price PC_{max} : Highest estimated purchase cost for a device PC_{min} : Lowest estimated purchase cost for a device IC: Installation cost categorical rating which is estimated based on the installation skill (IS) indicator. None: no installation required (1) Low: installation required by homeowner (0.75) Moderate: installation required by distributer (0.5) High: installation required by plumber or electrician (0.25) Very High: professional plumber and electrician are required (zero)		

Example

Device	PC	Norm PC	IC	CC
eSpring Model 100185 (100189)	950	0	0.5	0.167
GE PNRQ15FBL	390	0.736	0.5	0.657
GE GNSV70RBL	189	1	0.5	0.833
eSpring Model 100185 (100188)	950	0	0.75	0.25
Max	950			
Min	189			

<table>
<tr><td>Criteria Group</td><td>Economic</td><td>Objective</td><td>Minimize Life Cycle Cost</td></tr>
<tr><td>Indicator of</td><td colspan="3">Operating and Maintenance Cost</td></tr>
<tr><td>Description</td><td colspan="3">A quasi-quantitative assessment of the operating and maintenance cost of the treatment device.</td></tr>
<tr><td>Evaluation</td><td colspan="3">There are three parameters used to calculate the indicator:
1) The estimated purchase cost of the treatment device's replacement components per unit of treated water
2) The estimated cost of electricity consumed by the device
3) The estimated cost of service calls for the device

The rescaling and weighted sum equation used to calculate the indicator
Operating and Maintenance Cost $OC = \frac{2}{5}\frac{RC_{\max} - RC}{RC_{\max} - RC_{\min}} + \frac{1}{5}EC + \frac{2}{5}SC$

RC: estimated cost for a device replacement components (CAD) divided by the service life of the device
RC_{max} : Highest estimated replacement components cost for a device per unit of service life
RC_{min} : Lowest estimated replacement components cost for a device per unit of service life
EC: categorical rating of energy cost
None: no energy used (1)
Low: low energy consumption (0.75)
Moderate: moderate energy consumption (0.5)
High: high energy consumption (0.25)
Very High: very high energy consumption (zero)
SC: service cost categorical rating depending on whether or not the device requires service calls (Yes/No, 0/1)</td></tr>
<tr><td>Example</td><td colspan="3"><table>
<tr><th>Device</th><th>RC</th><th>EC</th><th>SC</th><th>OC</th></tr>
<tr><td>eSpring Model 100185 (100189)</td><td>0.04</td><td>0.75</td><td>1</td><td>0.95</td></tr>
<tr><td>GE PNRQ15FBL</td><td>0.05</td><td>1</td><td>1</td><td>0.89</td></tr>
<tr><td>GE GNSV70RBL</td><td>0.08</td><td>1</td><td>1</td><td>0.6</td></tr>
<tr><td>eSpring Model 100185 (100188)</td><td>0.04</td><td>0.75</td><td>1</td><td>0.95</td></tr>
<tr><td>Max</td><td>0.08</td><td></td><td></td><td></td></tr>
<tr><td>Min</td><td>0.04</td><td></td><td></td><td></td></tr>
</table></td></tr>
</table>

Criteria Group	Economic	Objective	Minimize life Cycle Cost
Indicator of	Bulk Purchase Discount		
Description	A quasi-quantitative assessment of a potential quantity discount on the treatment device bulk purchase		
Evaluation	Since quantity discounts are partly expressions of cost savings and partly of a promotional nature, it is not possible to lay down any general principles for the determination of their magnitude. However, on the assumption that the cost of obtaining an order changes with order volume, consequently the discount levels tend to increase quite steeply between the smaller order bands but then become relatively small at the higher levels. Default discount levels are assigned to the indicator's calculation, and users can change these default values through the knowledgebase editor. Orders below 2,000 CAD are given a discount of zero% (BPD = 0) Orders above 2,000 CAD are given a discount of 10% (BPD = 0.29) Orders above 5,000 CAD are given a discount of 25% (BPD = 0.71) Orders above 10,000 CAD are given a discount of 30% (BPD = 0.86) Orders above 20,000 CAD are given a discount of 35% (BPD = 1) Although this seems to be a static discount system, when it is applied to all devices the range of unit price for the various devices adds a dynamic nature to the discount estimation.		
Example	For a bulk purchase of 20 units		

Device	Order Value (OV) CAD		BPD
	Unit	Total	
eSpring Model 100185 (100189)	950	19000	0.86
GE PNRQ15FBL	390	7800	0.71
GE GNSV70RBL	189	3780	0.29
eSpring Model 100185 (100188)	950	19000	0.86

Criteria Group	**Environmental**	**Objective**	**Minimize Resource consumption**
Indicator of	**Energy Use**		
Description	A qualitative assessment of the energy used by the treatment device to treat water		
Evaluation	Categorical rating of the indicator of Energy Use (EU) None: no energy used (1) Low: low energy consumption (0.75) Moderate: moderate energy consumption (0.5) High: high energy consumption (0.25) Very High: very high energy consumption (zero)		
Example	**Device**	**Treatment Train**	**EU**
	eSpring Model 100185 (100189)	PPF-PPF-SBAC-UVB	0.75
	GE PNRQ15FBL	SBAC-RO-SBAC	1
	GE GNSV70RBL	SBAC-SBAC	1
	eSpring Model 100185 (100188)	PPF-PPF-SBAC-UVB	0.75
	PPF = Particulate pre-filter, SBAC = Solid Block Activated Carbon UVB = Ultraviolet disinfection class B, RO = Reverse Osmosis		

Criteria Group	**Environmental**	**Objective**	**Minimize Resource consumption**
Indicator of	**Chemical Use**		
Description	A qualitative assessment of chemicals used by the treatment device to treat water		
Evaluation	Categorical rating of the indicator of Chemical Use (CU) None: no chemicals used (1) Low: chemicals used are of small quantity (0.75) Moderate: chemicals used are of moderate quantity (0.5) High: chemicals used are of larger quantity (0.25) Very High: chemicals used are of very large quantity (zero)		
Example	**Device**	**CU**	
	eSpring Model 100185 (100189)	1	
	GE PNRQ15FBL	1	
	GE GNSV70RBL	1	
	eSpring Model 100185 (100188)	1	
Comments	Since most treatment devices do not use chemicals in the treatment process, it is likely that this indicator will be deemed redundant.		

Criteria Group	**Environmental**	**Objective**	**Minimize Environmental Footprint**
Indicator of	**Solid Residuals**		
Description	A quasi-quantitative assessment of the production of solid waste by the treatment device		
Evaluation	Three parameters influence the rating of solid residuals: 4. Whether or not there is a target contaminant (TC) to be removed from the source water. Target contaminant is defined as a contaminant that exists in a concentration that is higher than the maximum permissible concentration as defined by regulations in Canada or the United States. 5. The presence of any hazardous substance (HS) in the non-water contacting device materials (e.g. mercury in UV lamps). 6. Quantity of solid residuals (SQ) produced indicated by the total volume of the device's replacement components divided by its service life in liters. The value is then normalized against the range between the maximum and the minimum. The normalized values smaller than 1/3 get a rating of "low quantity", those between 1/3 and 2/3 get a rating of "moderate quantity" and those higher than 2/3 get a rating of "high quantity". Categorical rating of the indicator of Solid Residuals (SR)		

TC	HS	SQ	SR
-	-	No Residuals	None (1)
No	No	Low quantity	
No	No	Moderate quantity	Low (0.75)
Yes	No	Low quantity	
No	Yes	Low quantity	
Yes	Yes	Low quantity	Moderate (0.5)
No	No	High quantity	
Yes	No	Moderate quantity	
No	Yes	Moderate quantity	
Yes	Yes	Moderate quantity	High (0.25)
Yes	No	High quantity	
No	Yes	High quantity	
Yes	Yes	High quantity	Very High (0)

Example

Device	TC	HS	SQ	SR
eSpring Model 100185 (100189)	Yes	Yes	Low	0.5
GE PNRQ15FBL	Yes	No	Low	0.75
GE GNSV70RBL	Yes	No	High	0.25
eSpring Model 100185 (100188)	Yes	Yes	Low	0.5

Criteria Group	Environmental	Objective	Minimize Environmental Footprint
Indicator of	Liquid Residuals		
Description	A qualitative assessment of the treatment device production of liquid waste		
Evaluation	Three parameters influence the rating of liquid residuals: 1) Whether or not there is a target contaminant to be removed from the source water. Target contaminant is defined as a contaminant that exists in a concentration that is higher than the maximum permissible concentration as defined by regulations. 2) Type of system receiving the liquid waste (domestic sewer, tile, or septic tank) 3) Volume of liquid residuals produced Categorical rating of the indicator of Liquid Residuals (LR) None: no liquid residuals (1) Low: No target contaminant + low or high volume of liquid residuals + a domestic sewer management system (0.75) Moderate: Target contaminant + low volume of liquid residuals + a domestic sewer management system (0.5) High: Target contaminant + high volume of liquid residuals + a domestic sewer management system (0.25) Or No target contaminant + low or high volume of liquid residuals + Tile or septic tank sewer system (0.25) Very High: Target contaminant + low or high volume of liquid residuals + Tile or septic tank sewer system (zero)		
Example	Example lead as a target contaminant and domestic sewer		

Device	Volume of Residual	LR
eSpring Model 100185 (100189)	None	1
GE PNRQ15FBL	High	0.25
GE GNSV70RBL	None	1
eSpring Model 100185 (100188)	None	1

Criteria Group	Socio-cultural	Objective	Maximize Consumer Acceptance
Indicator of	Aesthetics		
Description	A qualitative assessment of aesthetic issues associated with water produced by the treatment device		
Evaluation	Depending on the treatment processes involved in the treatment device, examples for issues associated with the water produced are warm or low pressure water. The indicator of aesthetic water quality depends on two parameters (1) the severity (SV) of the issue (minor or major), and (2) the duration of the issue (DR) (temporary or lasting) Categorical rating of the indicator of Aesthetics (AS) None: no aesthetic issues (1) Low: minor and temporary aesthetic issues (0.75) Moderate: minor and lasting aesthetic issues (0.5) High: major temporary aesthetic issues (0.25) Very High: major and lasting aesthetic issues (zero)		
Example	(see table below)		
Comments	Aesthetic issues do not include the typical issues associated with source water, such as taste or odor, because these are considered contaminants in POU/POE treatment and devices are certified for removing them, and are employed in the screening rules to shortlist the feasible alternatives.		

Example:

Device	Issue	SV	DR	AS
eSpring Model 100185 (100189)	None	-	-	1
GE PNRQ15FBL	Low Flow	Minor	Lasting	0.5
GE GNSV70RBL	None	-	-	1
eSpring Model 100185 (100188)	None	-	-	1

Criteria Group	**Socio-cultural**	**Objective**	**Maximize Consumer Acceptance**
Indicator of	**Configuration**		
Description	A quasi-quantitative assessment of the degree of consumers satisfaction with the treatment device configuration		
Evaluation	There are a limited number of configurations for the treatment devices. The indicator is calculated for each configuration type based on the number of certified devices that are of the same configuration. The assumption here is that manufacturers will certify products that have more potential to meet consumer satisfaction. The value is then normalized against the range between the highest and lowest numbers of certified devices under any of the configuration such that the indicator ranges from 0 to 1. The rescaling equation for calculating the indicator of Configuration (CN) is: Configuration $CN = \dfrac{NC - NC_{\min}}{NC_{\max} - NC_{\min}}$ NC : number of certified treatment devices of a configuration type NC_{max} : Highest number of certified treatment devices of a configuration type NC_{min} : Lowest ratio of certified treatment devices of a configuration type		

Configuration Type	NC	CN
Point-of-Entry	127	0.074
Counter-top connected to sink faucet	121	0.071
Counter-top connected manual fill	6	0.000
Faucet mount	51	0.028
Plumbed in	1637	1.000
Plumbed in to separate tap	617	0.375
Pour through	40	0.021
Refrigerator filter	52	0.028

Example

Device	Configuration	CN
eSpring Model 100185 (100189)	Plumbed in to separate tap	0.375
GE PNRQ15FBL	Plumbed in to separate tap	0.375
GE GNSV70RBL	Plumbed in to separate tap	0.375
eSpring Model 100185 (100188)	Counter-top connected to sink faucet	0.071

Criteria Group	**Socio-cultural**	**Objective**	**Maximize Consumer Acceptance**
Indicator of	**Cosmetics**		
Description	A qualitative assessment of the attractiveness and communication features of the treatment device to the user		
Evaluation	Two parameters are considered in calculating the indicator: 1) Device decorative shape and color varieties 2) Display of device performance The weighted sum equation: Cosmetics $CM = \frac{1}{2}SH + \frac{1}{2}DP$ SH: a categorical rating of the attractiveness of the shape of the device None: device is available in one shape and color with no decorative attention (zero) Low: device is available either in more than one shape or color with no decorative attention (0.25) Moderate: device is available in one shape or color and with decorative attention (0.5) High: device is available either in more than one shape or color and with decorative attention (0.75) Very High: device is available in more than one shape and color and with decorative attention (1) DP: a categorical rating of the device performance display None: no display Or basic display in the form of instructions with insufficient information (zero) Low: device has basic display in the form of instructions with sufficient information (0.25) Moderate: device has electronic display or electronic interactive display with insufficient information (0.5) High: device has electronic display with sufficient information (0.75) Very High: device has electronic interactive display with sufficient information (1)		
Example			

Device	SH	DP	CM
eSpring Model 100185 (100189)	0.5	1	0.75
GE PNRQ15FBL	0	0.5	025
GE GNSV70RBL	0	0.5	0.25
eSpring Model 100185 (100188)	0.5	1	0.75

<table>
<tr><td>Criteria Group</td><td>Socio-cultural</td><td>Objective</td><td>Maximize Product Availability</td></tr>
<tr><td>Indicator of</td><td colspan="3">Market Availability</td></tr>
<tr><td>Description</td><td colspan="3">A qualitative assessment of the market availability of the treatment device</td></tr>
<tr><td>Evaluation</td><td colspan="3">Two parameters were considered in the indicator calculation
1) Chain stores coverage, and 2) Online and phone ordering
The weighted sum equation is: Market Availability $MA = \frac{1}{2}CS + \frac{1}{2}OP$
CS: a categorical rating of coverage of chain stores
None: not sold in chain stores (zero)
Low: sold in manufacturer's stores or other stores with low coverage (0.25)
Moderate: either sold in manufacturer's stores and other stores with low coverage or sold in manufacturer's stores or other stores with moderate coverage (0.5)
High: either sold in manufacturer's stores and other stores with moderate coverage or sold in manufacturer's stores or other chain stores with high coverage (0.75)
Very High: sold in manufacturer's stores and other chain stores with high coverage (1)
OP: a categorical rating of ease of ordering online or by phone
None: not sold online or by phone and no website (zero)
Low: not sold online but either (sold by phone + no website) or (not sold by phone + website) or (sold by phone + website with insufficient description) (0.25)
Moderate: either (sold by phone+ website with sufficient description) or (not sold by phone + sold online with insufficient description) (0.5)
High: either (sold online + not by phone + with sufficient description) or (sold online + by phone + insufficient description) (0.75)
Very High: sold online and by phone with sufficient description (1)</td></tr>
<tr><td>Example</td><td colspan="3">
<table>
<tr><th>Device</th><th>CS</th><th>OP</th><th>MA</th></tr>
<tr><td>eSpring Model 100185 (100189)</td><td>0</td><td>0.75</td><td>0.375</td></tr>
<tr><td>GE PNRQ15FBL</td><td>0.75</td><td>0.75</td><td>0.75</td></tr>
<tr><td>GE GNSV70RBL</td><td>0.75</td><td>0.75</td><td>0.75</td></tr>
<tr><td>eSpring Model 100185 (100188)</td><td>0</td><td>0.75</td><td>0.375</td></tr>
</table>
</td></tr>
</table>

Criteria Group	Socio-cultural	Objective	Maximize Product Availability
Indicator of	Market Penetration		
Description	A quasi-quantitative assessment of the availability of other devices of the same treatment train as the treatment device in the market		
Evaluation	Since there are only a limited number of treatment trains, the values of the indicator are calculated for each train based on the number of units certified that has the same train. The assumption here is that the train with the highest number of certified treatment devices has successfully penetrated the market. The rescaling equation to calculate the indicator of Market Penetration is: Market Penetration $MP = \frac{TC - TC_{\min}}{TC_{\max} - TC_{\min}}$ TC : number of certified treatment systems that fit a treatment train TC_{max} : Highest number of certified treatment systems for a treatment train TC_{min} : Lowest number of certified treatment systems for a treatment train		
Example			

Device	Treatment Train	TC	MP
eSpring Model 100185 (100189)	POU-PPF-PPF-SBAC-UVB	2	1
GE PNRQ15FBL	POU-SBAC-RO-SBAC	1	0.5
GE GNSV70RBL	POU-SBAC-SBAC	1	0.5
eSpring Model 100185 (100188)	POU-PPF-PPF-SBAC-UVB	2	1
Max		2	
Min		0	

PPF = Particulate pre-filter, SBAC = Solid Block Activated Carbon

UVB = Ultraviolet disinfection class B, RO = Reverse Osmosis