INTEGRATING SUSTAINABILITY IN MUNICIPAL WASTEWATER INFRASTRUCTURE DECISION-ANALYSIS USING THE ANALYTIC HIERARCHY PROCESS

by

Hana Sherin Galal

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Abstract

New regulations from the Canadian Council of Ministers of Environment, released in 2009, require all wastewater treatment plants in Canada to produce effluent of secondary treatment levels. To comply with the new law, many Canadian municipalities using primary treatment plants must retrofit or renew their old systems. There is an increasing pressure from stakeholder groups and policy makers to select new infrastructure using triple-bottom-line (economic, environmental and social) analyses. The present study aims to illuminate how differing preferences among experts from different stakeholder groups influence what is considered to be the 'most sustainable' wastewater treatment system. Through the use of policy documents, academic literature, and the use of AHP (a decision support tool: Analytic Hierarchy Process) an objectives hierarchy was constructed. The objectives hierarchy was made up of four criteria and 13 indicators. Five wastewater experts were asked to use pair-wise comparisons to score the indicators and criteria of the constructed objectives hierarchy and provide their opinions on the same. In addition, four low foot-print wastewater treatment alternatives were selected for review. One of the participants was asked to rank the four alternatives with regards to their performance on the selected indicators. This ranking, in combination with the rankings of the indicators and criteria, previously made by the five experts, were used to indicate the preferred alternatives for each of the separate participants. Then, the overall prioritization of the alternatives was used to carry out a sensitivity analysis. In terms of results, this study of sustainability indicators for wastewater treatment selection showed that the most contentious indicators among those studied were *Initial Costs* and *Long Term Costs*, *Effluent Quality* and *Aesthetics*. Additionally, the study showed that the Sequencing Batch Reactor was identified as the 'most sustainable' alternative by the average scores of all five participants and separately by four of the five participants.

Preface

The University of British Columbia's Behavioral Research Ethics Board certified this thesis research as a 'minimum risk' study. Ethics certificate number: **H11-03514**

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List of Abbreviations

AHP - Analytic Hierarchy Process

BAF - Biological Aeration Filter

BOD - Biochemical Oxygen Demand

DM - Decision maker

GHG - Green House Gases

IRR - Integrated Resource Recovery

MCDM - Multi-Criteria Decision-Making

MV - Metro Vancouver

N - Nitrogen

P - Phosphorus

SF - Sustainability Framework

TBL - Triple Bottom Line

TSS - Total Suspended Solids

WWTP - Wastewater Treatment Plant

WWT - Wastewater technology

UN - United Nations

US EPA - United States Environmental Protection Agency

Glossary

Alternatives - the technological options, which will be ranked according to their performance on the indicators

Biosolids – Sludge from wastewater after it has been treated and stabilized

Conventional systems – Aerated sludge and trickling filter wastewater treatment systems

Criterion - the components, which make up a sustainable WWTP (the overall objective)

Indicators - the measurable components, which make up the criterion

Overall objective - the overarching ‘global’ goal for the decision-making process

Objectives Hierarchy - a framework with which to organize overarching objectives into different levels of sub-objectives with the aim of studying different alternatives

Wastewater Treatment Plant – a facility, which takes in wastewater and treats it to various levels of purity

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I dedicate my Masters thesis to my parents. It is only through their constant support and love that everything has been possible for me.

Chapter 1: Introduction

1.1 Upgrading Wastewater Treatment Infrastructure

On a daily basis, municipalities around the world face challenges with aging and inadequate infrastructure (Bakker and Cameron, 2002; Sahely, Kennedy, and Adams, 2005; Berndtsson and Jinno, 2006). In Canada, most wastewater treatment plants (WWTP) are based on fifty-year-old constructions and are in need of upgrades (Sahely et al., 2005). Time, money and space (Vanier, 2006), as well as fluid legal requirements (CCME, 2009), varying technological availabilities (Lundin, 2002; Dixon, Simon, and Burkitt, 2003; Metcalf and Eddy, 2003), and conflicting stakeholder values (Mallet, 2007; Singhirunnusorn and Stenstrom, 2009) make the implementation of these upgrades a complex matter.

In wastewater treatment analysis, there has been a recent development towards formalized decision-analysis processes that use situation-based indicators and decision support systems to help gain a better understanding of the differences among the specific stakeholders and their objectives and moreover, to evaluate the inevitable trade-offs (Keeney et al., 2006; Contreras et al., 2008; Singhrunnusorn and Stenstrom, 2009; Brunner and Starkl, 2004; Amajirionwu, Connaughton, and McCann et al., 2008; Lienert et al., 2011). For wastewater systems, some analyses have been made considering the performances of technologies in countrywide studies. These have supported the general understanding of how a WWTP might perform "overall" (Dixon et al., 2003; Muga and Mihelcic, 2008 pp 437; Singhirunnusorn and Stenstrom, 2009). This more general knowledge can be used as a base, and it can be adapted to individually cater to the demands of each municipality, as variations will occur within specific local conditions (Abu-Taleb, 2000; Foxon et al., 2002; Muga and Mihelcic, 2008; Singhirunnusorn and Stenstrom, 2009).

1.2 Canada's Wastewater Treatment

Countries around the world, including Canada, suffer from severely deteriorating infrastructure (Sahely et al., 2005; Mirza, 2007). Water and wastewater infrastructure make up approximately 30% of municipal physical infrastructure and has so far led to a deficit of over 31 billion dollars for Canadian municipalities (Mirza, 2007). Poor effluent quality from WWTPs has been one of the principal causes of water pollution in national lakes and rivers (Chambers et al., 1997; Metcalfe and Eddy, 2003; International Joint Commission, 2009).

The emerging international focus on sustainable development suggests that, in addition to economic values, decision support systems "should" be integrating environmental and social components when repairing or replacing infrastructure (Muga and Mihelcic, 2008 pp 438; Khan and Faisal, 2008; Bdour et al., 2009). It is not common practice for Canadian municipalities to use sustainability indicators. None-the-less, some local governments are in the initial phases of integrating sustainability into formalized decision-analysis processes for municipal-wide developments including wastewater treatment (Sahely et al., 2005; MV - SF, 2010; Burnaby, 2012; Surrey, 2012; Whistler, 2012). This can be seen through different types of municipal frameworks, which ask decision-makers to consider the success of potential alternatives in terms of satisfying the local definition of sustainability when studying an initiative.

In 2009, the Canadian Council of Ministers of Environment produced the *Canada-wide Strategy for the Management of Municipal Wastewater Effluent,* a document that made every Canadian municipality legally obliged to produce effluent at secondary treatment level or higher by 2030 (CCME, 2009; Morales and Öberg, 2012). For many Canadian municipalities this translated into upgrades of their existent primary wastewater treatment plants (WWTP). This simplified the decision-making process for the country's local and regional governments as it forces the municipalities to ask the crucial question of 'with what' they should upgrade/replace their now inadequate WWTPs rather than 'if' they should upgrade. As there are many different technologies available, an in depth understanding of both these technologies and the different stakeholder preferences has been suggested by researchers in order to select the most "defendable" alternative with the overall highest score (Van Moeffaert, 2002 pp 60).

In retrofitting or replacing their wastewater treatment plants many Canadian municipalities are confronted with the issue of space-constraints. For example, in Victoria (Stantec, 2009) and Metro Vancouver (Fidelis, 2011), British Columbia, the municipalities do not have enough land to treat biosolids next to their planned new wastewater treatment facilities. Limited space in Metro Vancouver is expected to "raise public concern" through the transportation of unstabilized biosolids for processing elsewhere (Fidelis, 2011 pp 44).

The development of low-footprint WWTP can be considered preferable for a variety of reasons. The rate of urban growth generally positively influences land prices. Numerous municipalities in Canada experience that have experienced high population growth have had the value of land increases (Capozza and Helsley, 1989; Statistics Canada, 2011). Additionally, some wastewater treatment infrastructure is on leased land, soon to be returned to First Nations communities (Fidelis, 2011; MV, 2010c). Unlike some European nations, and densely populated countries such as Japan, the issue of space-constraint in many parts of Canada is a relatively recent obstacle. These restrictions require the consideration of the less commonly used low-footprint technologies rather than the traditionally implemented trickling filters and aerated sludge (Sampa, 1995; Ng et al., 2007).

1.3 Aim

The present study aims to illuminate how differing preferences influence what is considered to be the 'most sustainable solution'. Using a sustainability framework, the study illuminates how different weights assigned to performance measures by different wastewater experts influence what is considered to be the 'most sustainable solution'.

More specifically, this study aims to answer the following questions:

- Which sustainability criteria and indicators are relevant for space-constrained municipalities in Canada?
- Which indicators are the most controversial between the experts selected?
- Which indicators do the experts consider the most important, overall?
- How do different experts justify their weighting?
- What are the main issues that underlie the differences between the experts?
- Do variations of the indicator weights influence what is considered to be the 'most sustainable' wastewater treatment plant?

Thirteen sustainability indicators were identified and five wastewater experts were asked to rank these according to their relative importance in fulfilling the overall goal of sustainable wastewater treatment, using the Analytic Hierarchy Process (AHP). An objectives hierarchy was created with an interpretation of sustainability for wastewater treatment, attempting to reflect experience of previous research and needs specified in government policies. The thirteen indicators selected for the objectives hierarchy were; *Initial Costs, Long Term Costs, Revenue, Effluent Quality, Sludge Quality, Greenhouse Gas Output, Land Area Use, Perceived Safety, Cultural Acceptance, Aesthetics, Flexibility, Simplicity and Reliability (see Figure 7).* The scores of the experts were compared in order to identify the indicators, which lead to the largest variations in scores. The experts interviewed included an Operations Supervisor, a Municipal Manager, a Provincial Consultant, a Provincial Decision Maker and an Academic Consultant.

The scores were reviewed along with explanations provided in interviews conducted with each of them. Throughout the study, the experts are referred to as both experts and participants.

In addition, four low-footprint wastewater technologies were selected. The four alternatives were sequencing batch reactors (SBR), biological aerated filters (BAF), membrane bioreactors (MBR) and vertical deep shaft bioreactors (VSBR). One of the five experts (the Academic Consultant) was asked to rank the technologies using the 13 indicators mentioned above. Through the use of the Analytic Hierarchy Process (AHP), the scores for each criterion and indicator from each respective expert were combined with the scores for the alternatives given by the Academic Consultant. The aggregation of scores using AHP identified which of the four solutions each of the experts considered the 'most sustainable'. The results showed that four of the five participants' scores indicated that the Sequencing Batch Reactor (SBR) was the 'most sustainable'. Only the Operations Supervisor's scores led to a preference for the Biological Aerated Filtration (BAF). This prioritization was influenced by the Operations Supervisor's focus on the *Environmental* and *Social* indicators. The overall average scores of the five participants also indicated the SBR as being the 'most sustainable' alternative for this study based on the indicators selected.

The results were used to distinguish differing points of view and to identify the most contentious indicators. Also, the combined score of this group of experts was used to identify the indicators that were considered to be the most important indicators overall. The conclusions draw on previous studies that argue that differences in indicator weights can develop from varying expertise and experiences as well as incomplete and inconsistent transfers of knowledge (Hinds and Bailey, 2003). In light of this literature and an analysis of the indicators that were given different weights, this study discusses in what way the experience, knowledge and implicit values of different stakeholders may influence their attitude towards proposed solutions.

1.4 Study Boundaries

Urban water systems consist of the interaction of water resources, interdependent government layers, technical infrastructure, policies, ownership, and systems users' needs, and demands (Lundin and Morrison, 2002; De Kruijf, 2007; Bernsson and Jinno, 2008). With the recognition of the systems' complexity, it is preferable to have explicitly defined boundaries over the "time and spatial horizons" in order to simplify research on the topic (Sahely et al., 2005 pp 73). This simplification allows for an easier discussion of the trade-offs experts are willing to make (Sahely et al., 2005; Berndtsson and Jinno, 2008; Muga and Mihelcic, 2008). The boundaries selected for a study also aim to express the overarching framework for the study analysis. This study was limited to what Lundin et al. (2000) call the "Second extension" as this includes the organizational needs and thus offers a more "complete view" of the system as compared to a more narrow focus, limited to the treatment facility per se (Lundin and Morrison, 2002 pp 149). Conceptually, this level of analysis is suitable also because it allows for a focus on wastewater treatment plants through their separation from drinking water. The so called "Third extension" is more holistic in that it includes the entire urban system and could thus provide a more holistic understanding of the situation, but such an analysis would include more components than needed for this study. For example, the "Third extension" approach would include the study of "chemical and energy suppliers" as well as the users and suppliers of the waste and solid waste handlers (Lundin and Morrison, 2002 pp 149).

This study is limited to space-constrained municipalities and focuses on the wastewater treatment process itself, from the influent entering the hypothetical WWTP to the release of the effluent from the WWTP's outfall. This approach infers that the current water and piping system are accepted as is, and the study only reviews alternative wastewater technologies.

As expressed by Larsen and Gujer (1997) and Lundin and Morrison (2002), time-scales are also important in the assessment of sustainability. The consideration of future generations and their needs is central in the understanding of the concept. Due to this, it must be clarified how many generations will be considered. Vanier (2006) suggests the use of three separate time horizons when considering wastewater facilities: 'Operational' (≈ 5 years), 'Tactical' (< 20 years) and 'Strategic' (>20 years). For my study I selected the Strategic time horizon of 50 years as recommended by Lundin and Morrison (2002). Each time period has different stakeholders and possibly conflicting sustainability goals as well (Lundin and Morrison, 2002; Vanier, 2006; Dixon and Fallon, 2008). Though, one hundred years would be considerate of more future generations, decision-makers may not have the resources or ability to consider or imagine such time horizons (Pigeon, 2001). When the time-scale becomes too large, any conclusions or actions may merely become symbolic (Simon et al., 2004).

1.5 Literature Review

This section provides a diagnostic literature review of academic publications on decision-analysis as well as of wastewater treatment. These two bodies of literature are reviewed alongside relevant grey literatures. Particularly, focus was allocated to decision-analysis and sustainability concepts, their backgrounds, as well as their more recent applications. Literature in the intersection between the two fields is used to develop a theoretical basis for this thesis.

1.5.1 Sustainable Development

The *Brundtland Report,* presented in 1987 by the UN World Commission on Environment and Development (WCED) expressed a new direction for the international economy. Titled *Our Common Future*, it presented the idea of 'sustainable development' to the public, and explained that in all development the welfare of future generations must also be taken into consideration. The *Brundtland Report* states that a development path is needed that encourages “sustained human progress not just in a few pieces for a few years, but for the entire planet into the distant future” (WCED, 1987 pp 12). Intergenerational justice, also understood as meeting “the needs of the present without compromising” (WCED, 1987 pp 15) the needs of those in the future, could only be accounted for if social and environmental factors were considered alongside financial ones (Loucks, 1997). These three objectives of sustainability - social, environmental and economic sustainability - make up what is now commonly accepted as the ‘triple-bottom-line’ (TBL) (Lundin and Morrison, 2002; Muga and Mihelcic, 2008).

It has been suggested that sustainable development also involves an appreciation of the trade-offs required among components of the TBL (Barbier, 1987; Haimes, 1992). Different people are willing to make different trade-offs, and this will have an influence on what decision is optimal given the circumstances (Keeney, 1992; Singhirunnusorn and Stenstrom, 2009). Through applications of this ideology, future citizens, marginalized citizens, as well as the environment, all become legitimate stakeholders to be involved in determining if a development project is the most sustainable (Haimes, 1992; Brunner and Starkl, 2004; Dabaghian et al., 2008).

Sustainable development is linked to more than the future-conscious use of resources. Urban sustainability is increasingly becoming a prominent component in sustainability discussions (Choguill, 1996). Since the 1960s, the world population has been rapidly urbanizing, and in 2009, for the first time in history, the world’s urban population outweighed the rural populace (UN, 2009). Projections made by the United Nations (2009) forecasted that in 2025, there could be 29 mega-cities (>10 million inhabitants) worldwide. This is an 8-city increase from 2009. Other studies suggest that by 2015 the world will already have 59 mega-cities

(Koetter, 2005). Therefore, municipal infrastructure that takes the triple-bottom-line (TBL) into consideration is argued to be a central component of sustainable development (Haimes, 1992; Muga and Mihelcic, 2008). Prior to the 1990s, however, this connection between infrastructure and the sustainability debate had rarely been made (Choguill, 1996).

1.5.2 Sustainable Wastewater Treatment

Agenda 21 on Environment and Development (UN, 1992) did not specifically deal with sustainability in sanitation, and it has been critiqued for a lack of principles that realistically can be applied to real-world situations (Larsen and Gujer, 1997). In the creation of their *Millennium Development Goals* (USGA, 2000), however, the UN had included a goal (Goal 7C) with an aim to tackle the 2.6 billion people in the world without access to sanitary waste disposal. As urbanization increases, the wastewater produced by municipal populations is expected to rise significantly (Sahely et al., 2005; Muga and Mihelcic, 2008). This, in turn, will place more pressure on the available wastewater treatment facilities.

Most urban areas in the developing and developed world today are suffering the consequences of previous short-sightedness and neglect that have contributed to leaking pipes, contaminated rivers, leaching of ground water and heavy metals in biosolids (Larsen and Gujer, 1997). The issue of sustainable urban water and sanitation systems raises difficult questions concerning choices of technology and conflicts of interests (Lundin et al., 1999). In addition to the repairs required on older systems, a great number of researchers advocate the integration of new technologies as well as new managerial schemes for WWTP upgrades to increase their sustainability (Otterpohl, 1997; Muga and Mihelcic, 2008).

One approach to more sustainable wastewater treatment systems, called Integrated Resource Recovery (IRR) in the World Bank (1987) report, embraces the idea of reducing and reusing what has commonly been discarded from WWTPs. A similar definition was used in a report produced in 2009 by the British Columbia Ministry of Community Development (MCD, 2009). In the B.C. document, examples are given on how waste can be moderated and reduced rather than disposed. The central thesis is that IRR supports sustainability by changing perspectives from removing waste for disposal to extracting resources for reuse, with a focus on energy, water, and nutrients.

Some IRR methodologies include the production of energy from wastewater heat, methane production, and biosolids incineration. Energy recovered from the waste stream thus has the potential to help a wastewater treatment plant to be carbon neutral as well as provide profits from excess energy sales. Additionally, effluent (cleaned wastewater) at an acceptable standard can be used for ground water recharge or considered for resale (MCD, 2009). The World Health Organization (WHO, 2006) predicted that by 2050, over 40% of the world's population will live in areas of water scarcity. Reuse of wastewater could become a major factor in protecting water scarce regions, but it has not yet become common practice in North America (Schaefer et al., 2004: Toze, 2006; Ying and Abbaspour, 2007). Effluent is generally reclaimed for use in industry or non-agricultural settings particularly in golf courses (Centre for Water Resource Studies, 1999; Schaefer et al., 2004). Public perception remains a barrier against its development (Schaefer et al., 2004). Resource recovery is argued to be paramount to future wastewater treatment developments (Lettinga, 1996) and to have the potential to conserve precious resources, such as water (Jewell, 1994).

The WWTPs in Canada requiring upgrades generally already have preliminary treatment and primary treatment technologies available in order to clean the wastewater. Wastewater from municipalities is usually made up of approximately 0.05% solid waste (Drinan, 2001). As shown in *Figure 1*, WWTPs that use primary treatment set up in the linear system are the most common in the developed world (Otterpohl, 1997; Menegaki et al., 2007). In this system, water, nutrients, and various other compounds are lost to rivers, lakes and oceans. This not only wastes freshwater supplies but has also has been known to cause mass degradation within coastal flora and fauna from low quality effluent (GTZ, 2001).

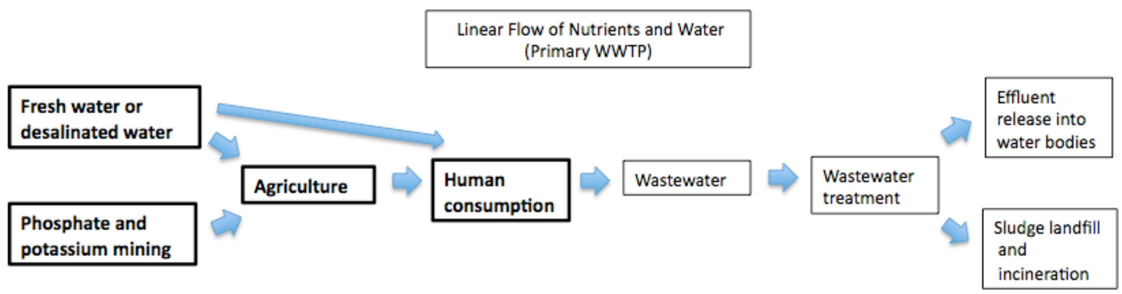


Figure 1 Linear Flow of Nutrients and Water - The arrows show the conventional, linear flow of nutrients and water found most commonly in the wastewater treatment of the developed world. The bold text on the left side of the figure indicates resources and their input into human systems, while the right side shows the outputs and attempted removal from the human system - adapted from (Otterpohl, 1997 pp 122)

Preliminary treatment or 'screening' removes organic or inorganic bulk components from the wastewater such as plastics and toilet paper, using a tight mesh screen (between 1.5 - 6mm for fine screens and larger than 6 mm for coarse screens) (USEPA, 2003). The collected grit is dried and compressed, and then usually transported to local landfills or incinerators (Sturman et al., 2004). The remaining wastewater is pumped towards a sedimentation tank. The next step is what is called 'primary treatment' though often preliminary treatment is considered part of the primary treatment process. Primary treatment is a gravity driven process that takes place in sedimentation tanks where oil and grease rise to the top, while heavier solids (grit) fall to the bottom. These heavier solids are removed from the wastewater, dried and compressed, forming sewage sludge or biosolids, and are often transported to local landfills or incinerators. Secondary treatment processes is the term generally used for any further treatment after primary treatment. Secondary treatment generally involves biological processes and filtration. Tertiary wastewater treatment is the highest level of wastewater treatment. It is often referred to as "effluent polishing" due to the high quality of the cleaned water released from the system (Metcalf and Eddy, 2003).

1.5.3 Multi-Criteria Decision-Making

Multi-criteria decision-making (MCDM) is the categorization of different decision methods developed for approaching decision-analysis problems, which deal with multiple and conflicting criteria. Different MCDM methods with varying mathematical sensitivities could lead to different end results and therefore, to different decision-making recommendations (Bottero et al., 2011). MCDM has been expressed as integral to the sustainability paradigm, as it supports the attempt to balance the demands of the triple-bottom-line (Haimes, 1992).

It is considered essential for decision makers to acknowledge that different stakeholders are bound to have different perspectives on a certain problem (Dunn, 1994; Funke and Jacobs, 2011). This perspective is particularly influenced by the social constructivist perspectives on organizations and society (Dunn, 1994). The most relevant MCDM techniques offer the ability to integrate different stakeholders and their subjective variations and a clear and systematic process as well. Due to this, it is believed that MCDM processes can "facilitate communication among decision makers and stakeholders" (Khan and Faisal, 2008 pp 1501), and decision makers and engineers (Anagnostoplous et al., 2007). Dery (2000) expressed that situations can only be defined by perceptions. These perceptions on existing situations, future developments and consequences are all highly subjective. Different studies define different stakeholder groups important to the decision-making process. Commonly used stakeholder groups are consultants, government members, NGO's, and academics (Dabaghian et al., 2008; Contreras et al., 2008;

Singhirunnusorn and Stenstrom, 2009; Botero et al., 2011). It is argued that interactive decision-making can lead to new "negotiated knowledge", and a new common ground, which could be even more important than selecting a definite best answer (De Kruijf, 2007 pp 32).

MCDM is a useful tool for urban water management as it allows for a simplification of what is generally considered a complex situation. Due to its simplification MCDM has the potential to improve the comprehension of a problem and its solutions (Keeney et al. 1996; Kolghi, 2001). Sustainability on the other hand is generally regarded to be a vague term (Muga and Mihelcic, 2008). As such, MCDM can be also be used to simplify sustainability into criteria and measurable indicators (OECD, 2001; Victoria Auditor General, 2004; Palme et al., 2005). Lindholm et al. (2007) suggested that all the data selected for analyzing the decision should be organized into a hierarchy and then aggregated in order to bring the analyst to the best possible results.

According to Guitouni and Martel, (1998), MCDM processes are usually set up with the following format (see *Figure 2)*. The OECD (2008) as well as other studies recommend a similar method to structure decision-making problems, articulate preferences, and aggregate scores while leaving room for iteration (Foxon et al., 2002). The revisions and improvements of the method should ideally take place through every step of the decision-making process, as well as be taken into consideration the consequences of the final decision (Fraser et al., 2003).

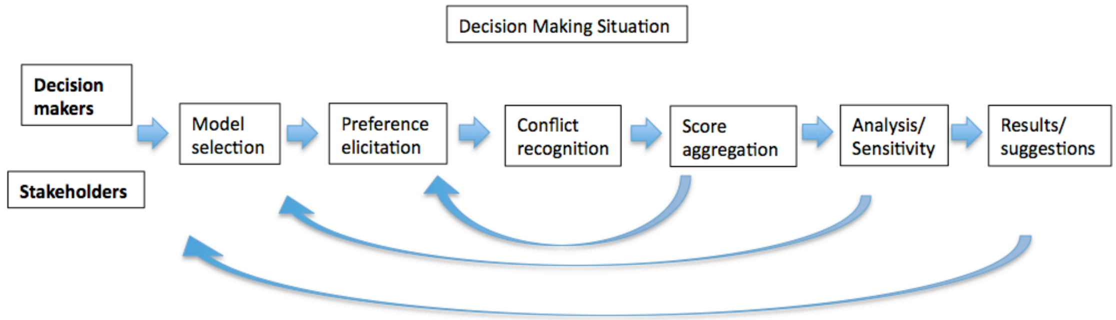


Figure 2 The Decision-Making Situation – It has been suggested that the process should be made up of different groups of people and multi-criteria decision-making is generally understood to have the step-by-step process seen above adapted from (Guitouni and Martel, 1998 pp 3)

In addition to deciding on the appropriate indicators, making 'good' decisions depends on selecting an appropriate decision-making methodology (De Kruijf, 2007; Rosen, 2009). There are a variety of different decision-analysis methods, systems, and software but there is no consensus on what method is the 'best', particularly when we think about different situational circumstances (Van Moeffaert, 2002; De Kruijf, 2007). There are, however, recommendations for the selection of an appropriate method for specific decision-making situations (De Kruijf, 2007).

- **Internally consistent** - the process must provide a logical soundness and clarity in throughout its process
- **Transparent** - the process should allow insight into the decisions made and the greatest influence on the suggested end result
- **Data requirement** - there must be a realistic understanding of what data exists and what data can be found in the time limits of the project
- **Simplicity, ease of use and software availability** - the decision-making tool must be useable and understandable by all stakeholders

- **Awareness of imperfections** - every model will bring slightly different results, and even the same model can bring different results for every different use

Similar descriptions of a good MCDM process can be found in the UNFCCC (2011) as well as other publications on decision model selection (Keeney, 1991; Van Moeffaert, 2002).

1.5.4 Selecting the Most Sustainable Wastewater Treatment Technology

Since the mid-90s, there has been an increase in studies developing and proposing methods to assess wastewater treatment plant alternatives. Many previous studies would today be considered incomplete or "one-dimensional" (Muga and Mihelcic, 2008 pp 438). The majority of studies in the 1970s and 1980s focused only on costs and effluent quality (Klemetson and Grenney, 1975). Even in more recent research, some studies have only analyzed single technologies (Nilsson and Bergstrom, 1995; Lundin et al., 1999). Others only assessed environmental issues and thus have neglected the expanding needs of society (Butler and Parkinson, 1997; Balkema et al., 2002; Lundin et al., 1999; Pahl-Wostl et al., 2011). The interaction between environmental and social goals is understood to be difficult to define (Mabee et al., 2003). Brunner and Starkl (2004) concluded that cost continued to be the focus of study even for some time after the *Brundtland Report*. They found that environmental and social concepts were primarily only integrated with "intuitive reasoning" that avoided the inclusion of clear processes (Brunner and Starkl, 2004 pp 441).

Political decision-making for wastewater infrastructure is very complex and difficult to replicate through models (Morales and Öberg, 2012). There are many different secondary and tertiary treatment systems to select from and thousands of potential ways in which they could actually be implemented. Each technology comes with its own benefits and costs, all objectively measurable and subjective (Balkema et al., 2002; Metcalf and Eddy, 2003). Higher levels of wastewater treatment offer more opportunities to fulfill IRR/sustainability ideals than primary treatment systems. Generally, technological selections are focused on water-based centralized sewage systems suited to the billions of dollars of infrastructure already in place (Wylie, 1996; Mirza, 2007). After consultations and alternative selections, final decisions for municipalities in British Columbia are taken on the Provincial level (Morales and Öberg, 2012). Various researchers have attempted to facilitate the process by increasing the transparency of the technological selection through the use of a range of decision-analysis methods (Keeney et al., 1996; Kolghi, 2001; Balkema et al., 2002; Bottero et al., 2011).

Keeney et al. (1996) conducted one of the earliest wastewater selection studies in North America. They found that assessing values among decision makers and stakeholders supported the evaluation of significant trade-offs between different alternative solutions. This includes the perspectives of different stakeholders on what a WWTP should deliver, as well as concrete information about regulations and resources available. Other studies suggest that a deeper understanding of conflicts can lead to better-organized and informed future decision-making environments supporting the study of pros and cons of different alternatives (Lipshitz and Strauss, 1997; Adgar, 2006). It is also suggested that feedback from experts is useful for "regulations to better adapt to the circumstances," and can be used to connect experts and other stakeholders with the public (Cedano and Martinez, 2010 pp 1).

Decision-analysis research on WWTPs and the integration of a sustainability framework is a relatively new research field, and much of the literature has focused on a broader understanding of how the decision-making processes work (Balkema et al., 2002; Karimi et al. 2011). These studies discuss potential methods and indicator selection, without discussing different scores of different participants. In some studies, stakeholders' interests are combined together for the selection of alternatives, without discussing how their different scores may change their preferred alternative. Either this is initiated through a physical gathering of people sharing scores and perspectives to come to a conclusion (Keeney et al., 1996; Compass, 2011), or data is gathered individually from participants and then combined mathematically (Singhirunnusorn and Stenstrom, 2009; Muga and Michelcic, 2008). Due to interests in collaboration leading to end results, there is sparse literature on how the conflicting indicator weights influence the preferred wastewater treatment technology. In wastewater, Mallet (2007), discussed how different understandings for what is important influences the preferred alternatives between different First Nations communities in Canada through the creation of a sustainability tool.

Researchers selecting waste and wastewater indicators using varied decision-making methods have used literature reviews (Singhirunnusorn and Stenstorm, 2009), grey literature (Muga and Mihelcic, 2008), and surveys or interviews of stakeholders (Amajirionwu et al., 2008). Indicators should preferably be suitable for the case study's geographic location, quantifiable, easy to understand, fulfill sustainability ideals, and be controlled in number (Muga and Mihelcic, 2008; Balkema et al., 2002; Singhirunnusorn and Stenstrom, 2009; Lundin et al., 1999). Over the last decade or so, it has become an accepted standard to use at least the triple-bottom-line (economic, environmental and social) to sort indicators for the evaluation of technologies regardless of the decision-analysis method in use. Some researchers have developed further, and added new components to this criteria list (Muga and Mihelcic, 2008; De Carvalho et al., 2009; Cedano and Martinez, 2010; Bottero et al. 2012).

Many WWTP selection studies select *Land Area* as an important indicator (Anagnostoplous et al., 2007; Dabaghian et al., 2008; Singhirunnusorn and Stenstrom, 2009; Fidelis, 2011). Metcalf and Eddy (2003) explain that technologies with smaller footprints allow for a more flexible use of the land. Many countries around the world experience issues with limited spaces. Particularly crowding in urban areas can require higher capacity WWTP (Will et al., 2008; Alan et al., 2008 Van Beelen, 2010). The use of the more expensive space-saving secondary treatment technologies and the study of their performance is a recent development in North America (Paul et al., 2004; Newman et al., 2005; Holakoo et al., 2006).

1.5.5 The Analytic Hierarchy Process

The MCDM method selected for this wastewater treatment selection study was the Analytic Hierarchy Process (AHP). AHP is a decision support model developed by Thomas L. Saaty in the 1970s. Since its development, AHP has become a decision-making tool, which has been implemented by both governments and businesses (Karapetrovic and Rosenbloom, 1999; Yan and Shi, 2002; Saaty, 2002; Khan and Faisal, 2007). It also fulfills guidelines by the UNFCCC (2011) on being a good MCDM process (*see section 1.5.3*). AHP has been used for infrastructure project prioritization (Ziara et al., 2002; Cedano and Martinez, 2010), and technological selections among silicon wafer slicing machines (Che-Wei et al., 2007). It has additionally been used in the comparisons between stakeholder preferences and consequent alternative ranking in waste and land policy research (Duke and Aull-Hyde, 2002; Contreras et al., 2008).

Researchers who have used AHP for wastewater treatment selection have found it to be an appropriate model to bring transparency to the wastewater treatment analysis with respect to the triple-bottom-line (Ellis and Tang, 1991; Dabaghian et al., 2008; Bottero et al., 2011). Ellis and Tang (1991) were one of the first to recommend AHP for addressing sustainability in wastewater infrastructure. Their case study included a selection of South East Asian nations. Other examples have followed from different places around the world, such as Zeng et al., (2002), Anagnostopoulos et al., (2007), Dabaghian et al., (2008), and Bottero et al., (2011).

Karimi et al. (2011) reflected that AHP was useful for representing the opinions of decision-makers. Dabaghian et al. (2008) expressed a satisfaction with the models ability to reflect the characteristics of wastewater-based problems.

A study on sustainable urban solid waste management used AHP to review and compare the objective weights and subsequent preferences of different stakeholders (Contreras et al., 2008). AHP was seen as useful in clearly showing different preferences and opinions. This is useful in decision-analysis as many indicators can be empirically measured, in “reality” (Saaty, 2008 pp 84) one must deal with imprecise data as well as potentially intangible opinions. Additionally, AHP helped show potential changes in the preferred alternatives depending on which stakeholder/expert/ranker has a “higher or lesser share” in the final cumulative score (Contreras et al., 2008 pp 988). For example, in their study the public or residents of a community expressed the opinion that health damage and GHGs were the most important indicators in selecting a waste management plan. Due to this, the publics’ overall preferred alternative was the plan with the lowest CO_2 output.

The decision-making technique, AHP, has three guiding principles: decomposition, comparative judgment, and synthesis of priorities (Saaty, 1987). The decision problem must be broken down into a hierarchy of objectives, also labeled as ‘criterion’ and ‘indicators’ with the alternatives as the lowest level of the hierarchy. An objectives hierarchy represents the subcategorized components believed to contribute to the overall goal of the study. The process of appraisal calculates from the lowest level of the objectives hierarchy, upwards, transforming the fragmented evaluations and data into an overall assessment (Saaty, 2002). The criteria and indicators are then ranked through pair-wise comparisons using a 1-9 and ½ to 1/9th scale representing their perceived importance in fulfilling their super-category (Saaty, 1994). More on AHP can be found in *Appendix E.*

Different researchers use different terms to describe the levels in which they break down their objectives hierarchies. Consequently, there can be confusion with terminology. At times 'criteria' is used for the categories within which 'indicators' are organized (Dabaghian et al., 2008; Zeng et al., 2007), other times 'indicators' are organized under the term 'components' (De Carvalho et al., 2009). 'Aspects' and 'principles' have also been used in the place of 'criteria' and 'indicators' respectively (Singhirunnusorn and Stenstrom, 2009), and there are further complications as more levels and decomposition takes place (Saaty, 2002). For this thesis, the terminology has been unified for clarity. The objectives hierarchy has been organized from top (broad) to bottom (specific) into the following four levels:

- **Overall objective -** the overarching 'global' goal for the decision-making process
- **Criterion** - the components, which make up a sustainable WWTP (the overall objective)
- **Indicators** - the measurable components, which make up the criterion
- **Alternatives** - the technological options which will be ranked according to their performance on the indicators

The most prominent criticism of AHP is centered on an issue of 'rank reversal' (Belton and Gear, 1983). This means that by adding another alternative to the selection of alternatives being evaluated, the ranking of two alternatives, not connected to the new input, can be reversed (Dyer, 1990; Schenkerman, 1997; Van Moeffaert, 2002). This can be seen particularly when a similar or duplicate alternative is introduced (Dyer, 1990). This has been expressed as a common problem of additive decision-making models (Harker and Vargas, 1987, Dyer, 1990). It has been found that the addition of new alternatives has the potential to change the ranks of other unrelated alternatives.

The addition or removal of alternatives can dilute scores through the fractions of weights distributed. This can be a source of rank reversal. Additionally, Dryer and Wendell (1985) believed that the 1 - 9 and ½ - 1/9 scale had no defendable reasoning, without a standard difference between each rank. This was presumed to make any results arbitrary and illogical. These scores, then given through pair-wise comparisons for each level of the hierarchy, also come with the disputed assumption that each criteria and each indicator is independent from the other (Belton and Gear, 1983; Dryer, 1990). This has been considered unrealistic (Dryer, 1990). Rank reversal goes against the MCDA ideal, which states that alternatives should ideally be independent of each other in their study.

The literature analysis supported the understanding of the field of wastewater treatment analysis and the extent to which AHP had previously been used in the selection between alternatives. Wastewater treatment selection studies have begun to integrate sustainability ideals through different methods and have lead to explicit insight into preferences and differences between treatment technologies. Clear distinctions had been made between AHP and other decision-making tools. The transparency of AHP and its ability to integrate both subjective ideas as well as objective data make it a preferable process to use.

Chapter 2: Methodology

The methodology used in the present study is based on guidelines from the Brundtland Commission inspired *Bellagio Principles*. The principles aimed to create a process that can answer research questions and support sustainability literature and ideals (Hardi and Zdan, 1997). The Bellagio Principles call for sustainability research to be guided by clear, holistic goals with clear, practical applicability. Consulting these guidelines, a methodology was created that allowed for a transparent review of decision-making for wastewater treatment alternatives. The analysis allowed for insights that may support future real life decision-making contexts.

The knowledge gained from literature analysis and policy reviews and publications on wastewater treatment was used in the creation of an objectives hierarchy suitable to the needs of this study investigating how different perceptions might influence judgment on what the 'most sustainable' solution is. Five wastewater experts from five different stakeholder groups were selected for this study. The experts were asked to rank different indicators using pair-wise comparisons and asked to think aloud while doing so. In addition, the experts were interviewed after the survey was completed. This chapter describes how the ranking, survey and interviews were performed, and how the results were used to identify and understand differences among the participants. This information was used to understand if components, which elicited highly varied scores, also had an influence on the relative preference scores of the alternatives. The alternative prioritization for each expert was also compared to see how their variations in indicator scores influenced their ranking of the four alternatives.

2.1 Documents

2.1.1 Public Documents

The criteria and indicators presented in a consultants report *Integrated Resource Recovery report for the North Shore* by the Fidelis Resource Group (Fidelis, 2011) were used to understand the decision-analysis method already utilized in space-constrained municipalities (*see Appendix* G). Documents detailing federal and provincial government wastewater guidelines were: the Canadian Council of Ministers of Environment *Canada-wide Strategy for the Management of Municipal Wastewater Effluent* (2009) and the British Columbia-wide *Environmental Management Act* (1999). Lastly, sustainability initiatives from municipalities throughout Canada were found by searching regional government websites (e.g., MetroVancouver, Metro Victoria, Whistler).

2.1.2 Peer-Reviewed Literature

The peer-reviewed literature was selected based on its relevance to the various fields integrated in this study. Searches were made in Science Direct, JSTOR and Google Scholar for papers on 'indicator selection for wastewater treatment', as well as those on 'decision-making theory'. The search was refined by using the key words 'sustainability indicators', 'wastewater treatment decision-analysis', 'space-saving WWTP' and 'decision-analysis'. Papers dealing with the use of AHP for wastewater technology decisions were identified through a search, using the keywords 'AHP' and 'wastewater treatment'. Additionally, interview methods were researched through searching 'Interview analysis' and 'Interview Protocols' to understand the advantages of various methods and what they could bring to an analysis. The reference lists of all papers were used for subsequent literature.

2.2 Selection of Indicators for the Objectives Hierarchy

An objectives hierarchy was created considering space-constrained Canadian municipalities, drawing on information collected in the peer-reviewed literature and public documents. The objectives hierarchy represents the information being used to study the wastewater treatment alternatives in an organized and categorized manner. The selection of the components of the objectives hierarchy was a top down process similar to the study by Pophali et al. (2007). The top level of the objectives hierarchy or the main objective represents the overall goal of a project. Each level below the main goal represents the sub-objectives (here referred to as the criteria and indicators) that should be considered in the fulfillment of the main goal. In this study the goal was to find the most sustainable wastewater treatment technology for a space-constrained Canadian municipality.

The second level of the objectives hierarchy constructed for the purpose of this study consisted of four criteria (*see Figure 7*). Drawing on literature in the field, the selected criteria were the TBL, *Economic*, *Environmental* and *Social*, plus the criterion *Technical* (Kholghi, 2001; Foxon et al., 2005; Van Moeffaert, 2002; Starkl and Brunner, 2004; Sahely et al., 2005; Singhirunnusorn and Stenstrom, 2009). The latter was included, as it has been considered effective in indicating the performance of mechanical operations. The criterion *Technical* is considered to be a way to monitor a technology's "ecological, environmental and engineering integrity" (ASCE/UNESCO, 1998) (*see Figure 7*).

The literature was also reviewed in order to find patterns of indicators proven useful in previous case studies with various stakeholders. The OECD (2008) and Keeney (1992) identified some criteria to be fulfilled in the creation of an objectives hierarchy; complete, non-redundant, measurable, independent (preferentially), and concise. To increase the simplicity and usability of the objectives hierarchy, thirteen indicators were selected as recommended by UNDPCSD (1995), Levett (1998), Hellstrom et al. (2000) and Lindholm and Nordeide (2007). Further details on the indicator selection process can be found in *Appendix H.*

For the purpose of the present study, easily comprehensible measures were selected from the literature to allow the interviewees to quickly grasp the concepts, as per recommendation by Vanier (2006). Information from the various sources were merged to create a suitable set of indicators that express the desire to minimize costs, energy use, land area use, loss of nutrients, aesthetic nuances, and to maximize resource recovery and societal acceptance (Nilsson and Bergstrom, 1995; Otterpohl et al., 1997; Hellstrom et al., 2000; Foxon et al., 2002; Balkema et al., 2002; Ujang and Buckley, 2002; Sahely et al., 2005; Muga and Mihelcic, 2008) (more details in *Appendix H*). Fulfilling these criteria is believed to lead technologies towards sustainability (Otterpohl et al., 1997). The creation of the hierarchy, however, comes with an understanding that the selection and interpretation of the indicators are context specific and are influenced by the interpretation of the researchers (Muga and Mihelcic, 2008).

2.3 Value Elicitation Interviews with Wastewater Experts

In June, July and August of 2012, five wastewater experts from different stakeholder groups were asked to rank the indicators and criteria of the objectives hierarchy prepared for this study (*see Figure 7* and *Appendix I*). The experts were selected from British Columbian municipalities experiencing space-constraints for their wastewater treatment technologies. One expert was a WWTP operations supervisor. The second expert was an academic involved in research in the field of civil/environmental engineering, but not in the day-to-day activities of a WWTP. The third interviewee was a manager from a municipal government. The fourth participant was from the provincial government and the last person selected was an environmental consultant to the provincial government. From here on, they will be referred to as; Operations Supervisor, Academic Consultant, Municipal Manager, Provincial Decision Maker and Provincial Consultant.

The interviewees were contacted by email. In the initial letter of contact the potential interviewees were given a description of the proposed session as well as an explanation for the study (*see Appendix A*). Upon expressing interest in participating in the study, the interviewees were emailed the consent form (*see Appendix B*). The participants were interviewed from the location of their choice and the survey link was emailed to them. Signed consent forms were collected at the beginning of the approximately one-hour-long meeting, which was tape-recorded. Each participant was given a survey guide that included a description of the model and the ranking process, the objectives hierarchy, as well as a description for each of the indicators (*see Appendix C).* After reviewing the survey-guide (*see Appendix C*) and given the opportunity to ask questions, the interviewees filled out the computer survey (through Expert Choice - *see Figure 4*) where they ranked all the indicators and criteria in the objectives hierarchy in pair-wise comparisons, using the 1-9 AHP format (see *Figure 3*).

1 Equally important
3 Moderately more important
5 Strongly more important
7 Very strongly more important
9 Extremely more important
2, 4, 6, 8 Intermediate judgment values

	1	**9**	**2,4,6,8**
Clarification	Components have the same importance in fulfilling the objective	One component is 9 times more important than the other in fulfilling the objective	To be used when your value falls between the main markers

Figure 3 The Score Range of the Pair-Wise Comparisons - The comparison between two different components of the objectives hierarchy uses AHP's 1-9 scale

They were asked to elaborate aloud on their scoring during the process. Attempts were made to keep the inconsistency ratio low by introducing the concept in the survey guide so that participants would be aware of the potential issue. Additionally, extra explanations were given for those who were less sure about the concept. Furthermore, the low indicator count assured less chance of inconsistent rankings. The participants were asked to rank the criteria in terms of their fulfillment of the overall objective, and the indicators in terms of their fulfillment of the criterion they were categorized under. The pair-wise comparisons were viewed in the same order by each of the participants *(see Figure 4).* Only one pair-wise comparison was displayed successively, to avoid confusion and distraction. At the end of each indicator set, the participants were asked if the end scores represented their opinions.

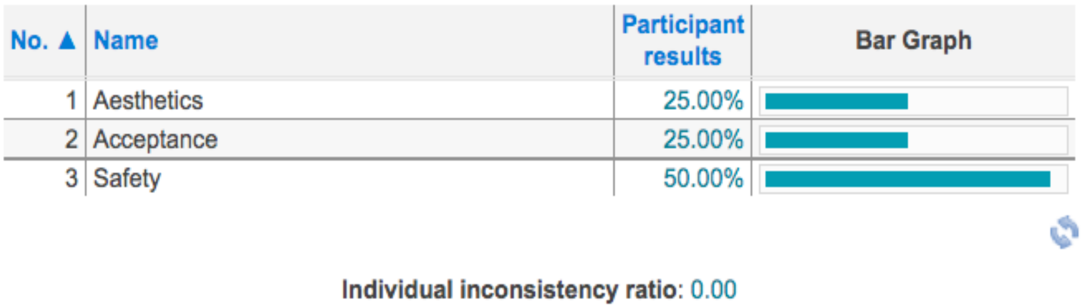
The interviewees were asked to verbalize their reasoning behind each ranking, while filling out the survey. This method is called Think Aloud Protocol (TAP), and it is believed to give deep cognitive insights as well as to assist in the comprehension of the participant's interactions with computers (Nielson et al., 2002; Magliano et al., 2010). The interviews were tape-recorded while the ranking exercises were recorded through the AHP program.

Figure 4 A Single Pair-wise Comparison Performed by the Municipal Manager – The comparison of two indicators organized under the criterion *Social.* Here the Municipal Manager selected 2 on the side of *Safety*. This expressed that from the perspective of the Municipal Manager, *Safety* was two times more important than *Cultural Acceptance* in terms of fulfilling the criterion *Social*

At the end of each 'set' of indicators, as well as at the end of the survey, the participants were asked various clarifying questions. The interviewees were asked questions like;

- "Why does this particular indicator stand out more than the others?"
- "What in your previous experience has led you to select these values?"
- "Do you think others in your field would feel similarly?"

After each set of indicators was ranked, the relative scoring was automatically visualized, as shown in *figure 5*. The numbers represent comparative importance, which the indicators were believed to have in the fulfillment of a single criterion.



No. ▲	Name	Participant results	Bar Graph
1	Aesthetics	25.00%	
2	Acceptance	25.00%	
3	Safety	50.00%	

Individual inconsistency ratio: 0.00

Figure 5 Weights of Indicator Set - Under the criterion *Social* the pair-wise comparisons of the indicators, expressed by the Municipal Manager lead to the end score seen above. *Safety* was the most important indicator for the Municipal Manager, and *Aesthetics* and *Cultural Acceptance* were felt to be of comparable importance

After all indicator and criterion scores had been discussed, the interview was concluded with questions about the objectives hierarchy itself. Similarly to a study by Hsu and Pan (2009), participants were asked questions regarding the completeness and usefulness of the objectives hierarchy (*see Appendix C*) and sustainability in wastewater management.

2.4 Comparison of Expert Weights and Indicator Identification

2.4.1 Consistency Ratio

In order to facilitate comparisons among the participants, a consistency analysis was carried out for each participant (Ellis and Tang, 1991; Foreman and Selly, 2002; Saaty, 2008). The interviewees were introduced to the idea of consistency before they began the survey and they were asked to think about the pair-wise comparisons, and the ranking to improve the final score, and the representation of their understanding. Interviewees with large inconsistencies (>0.1), were asked to renew their scores in order to increase the legitimacy of the end results as well as to more accurately portray their opinions, except in cases where the final ranking seemed to make sense, and it accurately represented the opinion of the interviewee. This happened a few times with the Operations Supervisor and Municipal Manager and once with the Provincial Decision Maker and Academic Consultant.

2.4.2 Indicator Score Comparison

The indicator/criteria ranking for each expert was graphed and compared. The indicators whose scores varied the most among the interviewees were selected for further analysis and the interviews were analyzed in order to better understand the reason behind the score variations.

After finding the indicators that had the highest discrepancies in their weights within each criterion, the adjusted weight was determined for each expert as well as overall (the weight of the indictor multiplied by the weight of its corresponding criteria) and used to create an overall ranking of all thirteen indicators. Once each participant's score was reviewed separately, the weights among the participants were compared as illustrated in *figure 6*.

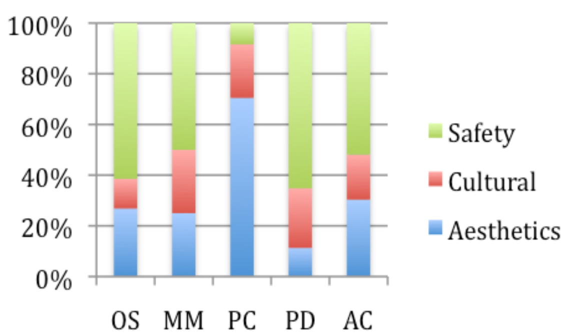


Figure 6 Scores of Five Experts for Social Criteria - The indicators *Safety*, *Cultural* and *Aesthetics* are organized under the criterion *Social*. The scores of each of the participants for each of the indicators are shown. For this criterion, four of the participants had very similar scores, however the Political Consultant had almost the opposite scores for Safety and Aesthetics.

The differences between the highest and lowest score were measured for each of the indicators. The most contentious indicators were defined as those that had the highest variation in score amongst the five participants.

2.4.3 Finding the Highest Scoring Indicators Overall

Subsequently, the scores of all the participants were combined to find the overall mean scores of the components of the objectives hierarchy. In *Table 1,* these scores are displayed with the adjusted weights of the indicators (the indicator score multiplied by its criteria score). The adjusted weights were used to rank all thirteen indicators. This information was then used to identify the indicators that had the highest ranking and thus considered to be most important *(Table 1).* As highlighted below, the indicators *Reliability, Effluent Quality, Sludge Quality, Initial Cost* and *Long Term Costs* were thought to be the most important overall by the five participants.

		Mean Scores	
Economic	0.23		
Environmental	0.33		
Social	0.16		
Technical	0.28		
	Weight	***Adj. Weight***	**Rank**
ECONOMIC		cri*ind	
Initial	0.40	0.092	5
Long term	0.44	0.101	4
Revenue	0.16	0.036	12
ENVIRONMENTAL			
Effluent	0.38	0.124	2
Sludge	0.31	0.102	3
GHG	0.13	0.043	11
Land use	0.18	0.060	8
SOCIAL			
Aesthetics	0.32	0.053	10
Cultural	0.22	0.036	12
Safety	0.45	0.074	7
TECHNICAL			
Flexibility	0.29	0.080	6
Reliability	0.52	0.147	1
Simplicity	0.19	0.054	9

Table 1 Mean Scores of All Experts for the Components of the Objectives Hierarchy

2.5 Selection of Alternatives

The literature on the comparative advantages of different wastewater treatment technologies was used to help select technological alternatives appropriate for the study. To increase the applicability of the study, four technologies were selected, of which none was the obvious best or worst performer for any of the selected indicators (Keeney et al., 1996; Clements, 2004). To increase the realism of the study, a Metro Vancouver executive was consulted regarding wastewater treatment systems of interest for Canadian urban municipalities.

Drawing on the literature and the advice provided, four technologies were chosen based on their low footprint, and their ability to produce high quality effluent (USEPA, 1982; Arora et al., 1985; Van Beelen, 2007). The four alternatives are all capable of treating residential wastewater to the level required by the 2009 CCME ruling; 25 mg/l BOD and 25 mg/l TSS. These limits are also suitable according to WHO (1997) standards for urban water reuse (washing/toilet/industry). All four technologies were also relatively new in terms of their utilization in Canada. At the same time, they have all been proven functional in different Canadian municipalities. Before proceeding, a literature review was conducted to assure that none of the four was recognized as the highest performer for each of the 13 indicators selected for the study (*see Appendix F*).

The four chosen alternatives were:

1. A **Sequencing Batch Reactor** (SBR), which is a technological alternative reviewed in Anagnostopolous et al., (2007) and Zeng et al. (2007). SBR systems have been developing all over Canada, one example being in Cardinal, Ontario where the SBR was easily adjustable and complied to the necessary standards in place (Premiertech, 2009).
2. A **Membrane Biological Reactor** (MBR), a system, which has been developed especially over the last 10 years (Ng et al., 2007). In Brandon, Manitoba an MBR entered service in 2012 in order to treat the wastewater of a growing population and a growing manufacturing industry (Journal of Commerce, 2011).
3. A **Biological Aeration Filter** (BAF) technology, was selected as it was compact, and it was successfully implemented in Kingston, Ontario in 2012 (Kingston, 2012).

4. A **Vertical Deep Shaft Bioreactor** (VSBR), which is a technology that has been successfully implemented at several locations in Canada, such as at an oil refinery in Burnaby, British Columbia (EC, 2010).

The collection of sub-objectives (*see section 2.2.)* was organized into an AHP hierarchy guided by the sustainability framework used by different Canadian municipalities (MV-SF, 2008, Surrey, 2012; Toronto, 2012). The alternatives selected for the study are the bottom (fourth) row of the objectives hierarchy. The AHP objectives hierarchy developed for the present study is illustrated in *Figure 7*.

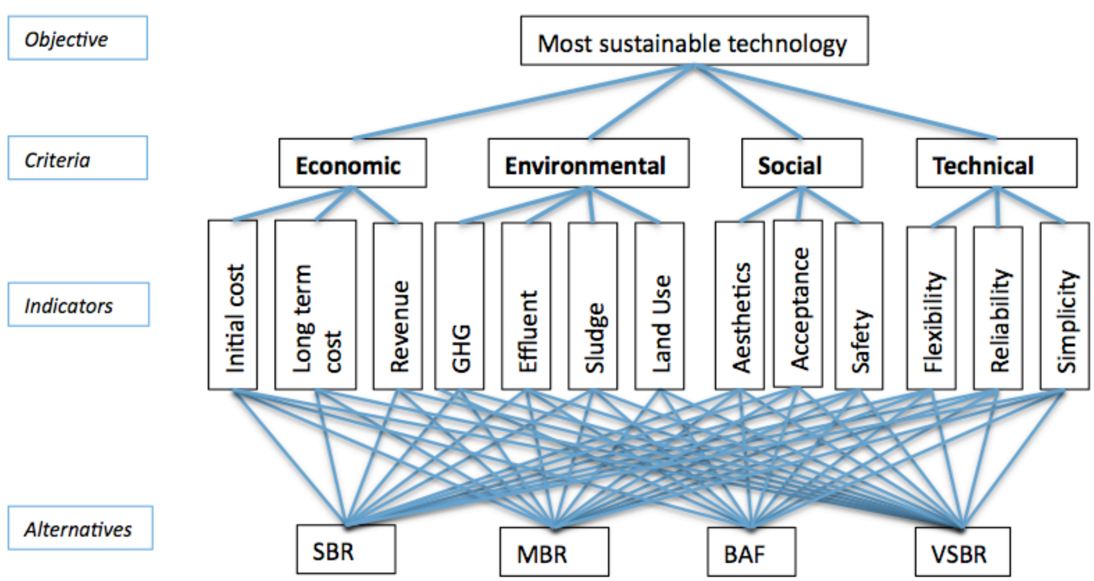


Figure 7 The Complete Objectives Hierarchy for This Study - The objectives hierarchy was developed in line with AHP standards to enable the identification of different preferences between experts. The objectives hierarchy is made up of objectives and sub-objectives, which will be used in order to rank the four alternative wastewater treatment systems

2.6 Scoring of Alternatives

In addition to filling out the survey and participating in the interviews described in section 2.3, one of the five experts, the Academic Consultant, was asked to rank the four alternative technologies with regards to their performance using the same 13 indicators. Only the Academic Consultant was asked to do the alternatives ranking, as the other participants did not have enough experience with, or information on all of the four technologies. This reflected real world decision-making contexts as often those making a decision have an understanding of what they want the end product to be, but must rely on consultants to provide and select the details according to the end goal. For each of the indicators, the Academic Consultant was asked to carry out pair-wise comparisons of the alternative technologies, using a computer based, automated survey. The Academic Consultant was emailed a survey guide (*see Appendix D*) as well as a link to the automated survey. In the survey they ranked the four wastewater treatment alternatives separately for their performance on each of the 13 indicators (*see Figure 8*).

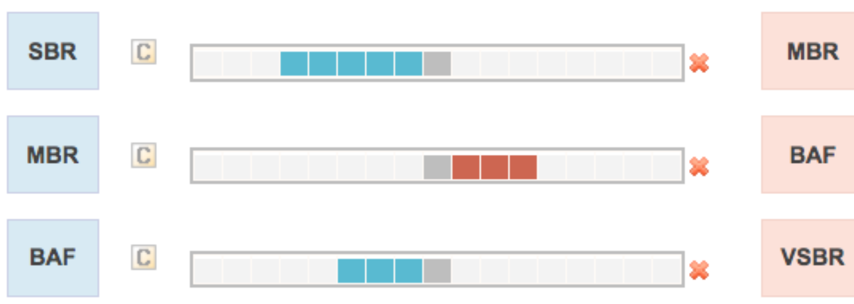


Figure 8 Pair-wise Comparisons for the Four Wastewater Treatment Alternatives - the figure shows their comparative performance on the indicator *Initial Cost*

The pair-wise comparisons then lead to a prioritization of each of the four alternatives for each of the 13 indicators of the objectives hierarchy (*see Figure 9*).

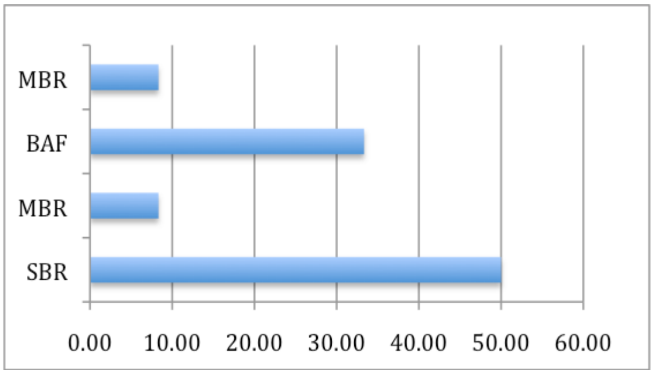


Figure 9 The Four Alternatives and their Performance for the Indicator *Initial Costs* - Here the Sequencing Batch Reactor (SBR) was the most preferred technology or the one with the lowest *Initial costs* in Canadian Dollars. These scores are according to the preferences of the Academic Consultant

2.7 Revealing the Most Sustainable Wastewater Treatment Alternative

The scores of the alternatives by the Academic Consultant were then combined with the separate indicator and criteria scores for each of the experts. This led to an identification of preferred alternatives for each of the experts. Following the calculations of the Analytical Hierarchy Process, the scores were aggregated through the different levels of the objectives hierarchy, from bottom to top. First, the scores of the alternatives for each of the indicators were multiplied with the weights given by the separate experts to the indicators. Then these scores were multiplied with the weight given to the super-category of the indicator (criteria). This led to the final end score of each of the alternatives, and their prioritization in terms of overall sustainability goal of the study *(see Figure 10).*

Figure 10 shows the ranking of the alternatives based on the rankings of the Municipal Manager.

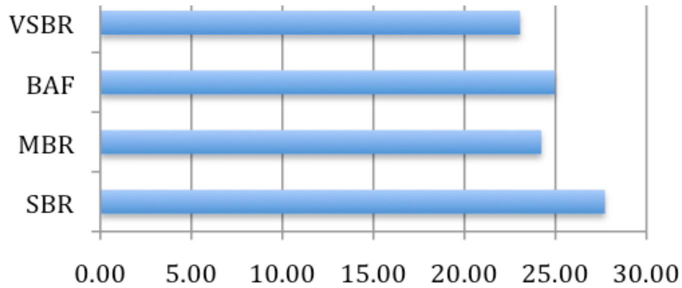


Figure 10 Ranking of Alternatives through Municipal Manager Indicator Scores - According to the criteria and indicator weights allocated by the Municipal Manager, the four alternatives had very similar final scores. The SBR was the 'most sustainable' wastewater technology, however, the other three alternatives are considered to have a near comparable overall performance

2.8 Sensitivity Analysis

The last step of the study involved a sensitivity analysis with a focus on the most contentious and the most important indicators. A sensitivity analysis can give insight into "how changes to input assumptions would change the result" (USEPA, 2001 pp 55). The sensitivity analysis was used to understand the extent to which the changes in weighting of the indicators affected the ranking of alternative preferences for the mean scores of all the experts. The selected indicators and criteria were assigned with lowest and highest scores and the influence on the preferred technology was recorded (Saaty, 1994; Anagnostoplous et al., 2007). In the final stage of the analysis, the results of the sensitivity analysis were used for a discussion based on the controversial indicators and on the extent of their influence on technological preferences.

Chapter 3: Results and Analysis

The five indicators with the overall highest weights (i.e. the most important) were (in decreasing order): *Reliability, Effluent Quality, Sludge Quality, Initial Cost* and *Long Term Costs (Table 1)*. The five indicators with the largest variation in scores (i.e. the most contentious) were (in decreasing order): *Aesthetics, Perceived Safety*, *Initial Cost, Long Term Cost and Effluent Quality,* suggesting that three of the indicators that were assessed as the overall most important were also the most contentious ones. This overlap seems to come from strong opposing views among the participants. For the three indicators *Initial cost, Long term cost* and *Effluent quality*, the scores varied between being considered to be the most important for the indicator set and the least important of the indicator set. In addition, the three overlapping indicators were from the criteria groups *Economic* and *Environmental*. The high average weights of these criteria also contributed to the high weights of the indicators.

On the other hand the criterion *Social,* had the average lowest score among the four criteria selected for this study. As a result the indicators *Perceived Safety* and *Aesthetics* were not in the first five highest ranked indicators. The participants, however, had the highest variations in score for the indicator *Aesthetics*. This made it the most contentious indicator in terms of the pair-wise comparisons. This suggested that there would potentially be the biggest misunderstanding between the participants on the importance of that indicator in the fulfillment of a sustainable wastewater treatment plant. Four of the five participants selected it as the least important indicator from the indicator set, and the fifth participant ranked it as the most important indicator of the *Social* indicator set. This, along with the low score of *Social*, led to *Aesthetics* overall low average score.

Below, the results are presented more in detail, starting with a discussion on the *Economic*, *Environmental*, *Social* and *Technical* indicators, in separate sections. The section on the *Economic* indicators focus on *Initial Cost* and *Long Term Cost*, the section on *Environmental* indicators focus on *Effluent Quality*, and the section on *Social* indicators focuses on *Aesthetics*.

Thereafter, the results of the analysis of the assessment of the four technologies are presented, including the results of the sensitivity analysis. The four alternatives are compared in terms of their performance on the four selected contentious criteria.

3.1 Weighting of Sustainability Indicators

3.1.1 Economic indicators

The indicators *Initial Costs* and *Long Term Costs* were two indicators with large differences between their highest and lowest scores *(see Figure 11*). This is similar to the results seen in Anagnastopoulous et al. (2007). In their study, high variations in score seemed to come from stakeholders who fund the facilities and so they believe construction costs represent a higher weight. This suggests that the proximity to the actual budgeting process increases its importance in the eyes of the participant. This can be reflected in the scores seen in this project, where the two lowest scorers of *Initial costs* were the Provincial Decision Maker and the Operations Supervisor. Both of these experts were not involved with the distribution or requesting of funding for the creation of a WWTP, but rather experienced the consequences of cost cutting measures on a daily basis.

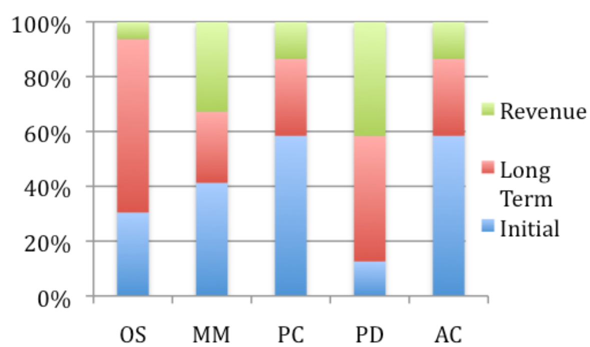


Figure 11 Expert Scores for Criteria Economic - With the indicators under the Economic criterion, Initial Costs had the highest variation in score, the Political Decision maker found Initial costs to be of lowest importance, while the PC and AC had equally high scores

While three participants ranked *Initial Costs* as most important of the three indicators, the Provincial Decision Maker and the Operations Supervisor believed that *Long Term Costs* were more important since maintenance costs are high, and accumulate continuously. These preferences were clear through the scores of the ranking exercise. Additionally, in the interviews, the two participants argued that more expensive technologies would perform for a longer time period at a higher quality and this would ultimately decrease the long-term operations complications and maintenance costs. Considering more expensive technologies as more sustainable contradicts much of the focus of wastewater treatment research (Ellis and Tang, 1991; Sahely et al., 2005).

Generally, studies on public infrastructure attempt to keep costs low, in order to keep taxes low as well as allow for other public investments. Many studies on wastewater treatment technology selection develop with the assumption that low costs are a central attribute of an appropriate wastewater treatment system (Starkl and Brunner, 2004; Sahely et al., 2005; Guanming, 2007; Anagnostopoulos et al., 2007: Dabaghian et al., 2008; Bottero et al., 2012).

In particular, the perspective of the Provincial Decision Maker reflects on insights also expressed by Ujang and Buckley (2002). The Provincial Decision Maker stated that the benefits, people can receive in the long run show that over-budget projects, lead to a "better outcome for sustainability". In connection to this they explained;

"…if you are talking about sustainability I certainly don't think it's an issue spending more money up front if you can justify the long term… and have something more energy efficient… "

Provincial Decision Maker, 2012

Similarly, Ujang and Buckley (2002) express through the use of the sustainability framework that even if financial costs are high, advanced technologies may not be considered expensive when public health and environmental quality are included in a cost benefit analysis. There has been an increase in recognition of the advantages of clean water, and the long-term positive influences of high quality effluent (Ujan and Buckley, 2002).

The ranking exercise confirmed that the Provincial Decision Maker did not view high *Initial Costs* as a problem. His score on *Initial Cost* was the lowest from the five experts. The interview revealed that the Provincial Decision Maker was familiar with the financial backup systems for vital infrastructure in British Columbia. He argued that this safety net would be able to protect a WWTP if the investment went over-budget. Contrary to the perception of the Provincial Consultant and the Academic Consultant, the Provincial Decision Maker believed that larger initial financial commitments had the potential to lead to a more sustainable technology through reduced *Long Term Costs.* The Provincial Decision Maker also held the view that these high *Initial Costs* should be carried by the society as a whole.

"…there is a good argument that even if the cost is quite high, that society as a whole should bear that costs to provide that piece of infrastructure or whatever it is to achieve the goal of sustainability."

Provincial Decision Maker, 2012

The Operations Supervisor also gave a lower weight to *Initial Costs* in the ranking exercise. The Operations Supervisor believed that there was always "a way to loosen pockets" (OS, 2012) to ensure that society continued to be provided for with high quality wastewater treatment. The Operations Supervisor argued that quality of the WWTP should not be jeopardized due to price issues, though he was aware of the needs of the taxpayers.

"… it's sometimes a painful pill to swallow for these projects…. But for the end result it's necessary, so there is a pretty substantial financial commitment to make, that's just the way it is."

Operations Supervisor, 2012

Ellis and Tang (1991) expressed the issue of understanding a publics willingness to pay for a facility as vital in the decision-making process.

In contrast to the two mentioned interviewees, the remaining three interviewees gave a high rank to having low *Initial Costs*. The participants expressed their views from polarized sides of the debate on costs. Both sides suggest that their way of decision-making is the cheapest overall. Interestingly, even though the Municipal Manager argued that low costs were not the most important component of sustainable wastewater treatment, this person ranked *Initial Costs* as the most important *Economic* indicator. The Municipal Manager based this ranking on the argument that a low *Initial Cost* is vital for the budget. The Municipal Manager explained that,

"…once you get the initial capital costs to build, then the other ones fall into place…"

Municipal Manager, 2012

Additionally, the Municipal Manager felt that decision makers needed to keep the public in mind. For this reason, he gave the *Initial Costs* and *Revenues* very similar scores. If high *Revenues* could even out high *Initial Costs*, the public would be "a little less frantic" (MM, 2012). This shows in the perspective of the Municipal Manager that the public was most concerned with immediate costs, but could be calmed by the promise of a financial return in the future. There was, however, no mention of the public's concern with *Long Term Costs*. This is a previously documented phenomenon, especially in the field of climate change. Research in this field points towards the difficulty of raising public awareness for issues with long-term risks and consequences (Weber, 2006).

During the interview, the Provincial Consultant insisted that the *Initial* and *Long Term Costs* of the project were two of the most important indicators of the entire established objectives hierarchy. The Provincial Consultant expressed that sustainability was primarily an *Economic* issue, where each of the thirteen indicators would need to be valued appropriately and included in a hypothetical budget. This expert said, "climbing over that hill (*Initial Costs*) is very important for moving forward". Similarly to the Municipal Manager, the Provincial Consultant believed if a WWTP was financially viable, the other components could be adjusted where needed. In contrast to the Provincial Decision Maker, the Provincial Consultant believed that most costs were in the construction and setup, while operations and maintenance were relatively inexpensive. The Provincial Consultant explained that he had "seen projects fail" because of problems with their cost and the pressures behind delivering a service. He had, however, rarely seen failures from technical problems.

Like the Provincial Consultant, the Academic Consultant expressed that *Economic* issues, (or the indicators organized under the criterion *Economic)* were the most important factors of the objectives hierarchy. Within this, the Academic Consultant highly prioritized *Initial Costs.* This showed similarities with the result from Singhirunnusorn and Stenstrom (2009), who found that their academic experts expressed higher priorities for the "affordability" of wastewater treatment, though for their study no explanation is given.

The Academic Consultant was emphasizing the importance of considering many different components. They felt, however, that as long as the technology followed the nationally/provincially set guidelines, all that really mattered was who (which consultant) could construct it for the lowest cost.

"At the end of the day the one who can do it at the lowest cost gets the contract…"

Academic Consultant (2012)

Though, the Academic Consultant was strongly in favor of more sustainable technology, that individual's experiences in consulting provided particular insights insights on the selection process behind wastewater treatment technologies. From his perspective, decisions on selecting WWTPs from within the government were primarily focused on the cost of developing and implementing the infrastructure. The Academic Consultant explained that a municipality would propose all the results they would want to see from a WWTP, and it was then up to the consultants to produce this at a low cost. This shows connections to the bottom up process used by Keeney et al. (1996) that organized the indicator selection processes, and used the results of that study to develop and select alternatives, which fulfilled the preferred indicators.

Overall the participants had varying views on the indicator *Revenue.* The Municipal Manager compared not reaching projected *Revenue* to going over budget on the *Initial Costs.* The Municipal Manager was the only participant who believed that *Revenues* were of equal value to the *Initial Costs*. On the other hand, the Provincial Consultant did not see any value in relying on *Revenue.* The low weight in the pair-wise comparison allocated by the Provincial Consultant reflected insights from the interview. They suggested that the technology to produce energy was potentially more expensive than the profits that could be made. The Operations Supervisor, however, gave the lowest score from the five participants for the indicator *Revenue.* The basis for this ranking was from their direct experience with WWTP *Revenues*. The Operations Supervisor expressed that WWTPs were rarely given direct access to these revenues to reuse for their operations and maintenance budgets. The participant believed that WWTPs themselves were disconnected from the business of selling extracted resources.

3.1.2 Environmental Indicators

Among the *Environmental* indicators, *Effluent Quality* elicited the largest difference in scores among the participants (see *Figure 12*). Though each expert believed that *Effluent Quality* was very important for the selection of a WWTP, the comparative weighting of the other indicators had a large influence in the end rank. In this study the *Effluent Quality* received varying scores through the pair-wise comparison exercise but seemed to elicit similar interview responses from the participants.

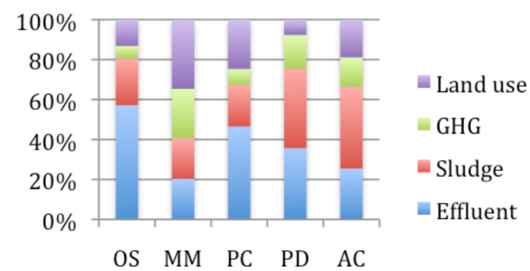


Figure 12 Expert Scores for Criterion Environmental - Effluent was the most contentious indicator between the four indicators under the criterion *Environmental*, GHG's had an overall low score from all the participants

The largest variation in scores was between the Operations Supervisor and the Municipal Manager (*Figure 12*). This difference seems to come from the fact that the Operations Supervisor saw *Effluent* as the main indicator of the *Environmental* indicators. The Operations Supervisor believed that a WWTP is directly responsible and accountable for making sure that effluent is safe to return to natural water bodies. The Operations Supervisor spoke in terms of permits, and fulfilling government regulations. They stressed that the *Effluent Quality* was constantly reviewed, and failures to comply led to penalties. As there are no limits with regards to GHG emissions and the control of the quality of the sludge is less stringent, they felt that these factors were less important for the sustainability of a WWTP. It seemed that the Operations Supervisor gave a higher importance to the indicators that had corresponding permits. Government regulations and subsequent punishments were in consideration during the discussion of sustainability. They also expressed that *Sludge* was generally not an immediate worry, and could be easily quarantined if it was of insufficient quality. For ranking *Effluent Quality* against *Sludge Quality* the Operations Supervisor explained,

"..if we don't meet this [permit for effluent quality], we get into a lot more trouble than if we don't meet the sludge…"

Operations Supervisor, 2012

The Operations Supervisor explained that for Greenhouse Gas emissions, there were no set regulations for output limits of a WWTP, as well as no repercussion for WWTPs that overproduced Methane or Carbon Dioxide (CO_2). The Operations Supervisor seemed to feel disconnected from the GHG issue.

"...GHG …. doesn't have a lot of weight on how we do our business… It's kind of a idealistic thing that we will say, it would be nice [to consider it]…"

Operations Supervisor, 2012

The Provincial Consultant ranked *Effluent Quality* with a similar score to the Operations Supervisor. The Provincial Consultant also verbalized his preference for this indicator and expressed,

"…effluent, you know that's the whole point of the wastewater plant, to make sure that the water is clean, if you don't get that done then people will ask why did you build a plant [WWTP] in the first place."

The Municipal Manager gave the lowest score for *Effluent Quality* through the pair-wise comparison exercise. In the interview, it became clear that this number did not come from a perceived unimportance of *Effluent Quality*, but rather came from the relative importance of the other three indicators. The Municipal Manager had the most balanced view in terms of the importance of each of the *Environmental* indicators. He explained that he wanted to "get it [the environment] back to neutral". The Municipal Manager saw each component of the *Environmental* criterion to be of equal importance in the ranking exercise. The focus of the discussion ultimately stayed on *Effluent* issues, due to the Municipal Manager's experience with sewage. They expressed that *GHGs* ideally would need more focus, and that education was key to reducing environmental problems. This expert was also the only one to perceive *GHG* and *Land Area Use* as directly related problems. The Municipal Manager also explained that a technology should not only be studied on its output as this study has done through the inclusion of *Effluent, Sludge* and *GHG's.* He explained WWTPs were also very sensitive to their inputs, and the Municipal Manager believed that lack of understanding of wastewater treatment plants, were a reason for environmental damage, not the incapability of the technology.

"The biggest concern is …. fats, oils and grease… it reduces the capacity of the system,.. there is a massive cost… everyday sewers back up…"

Municipal Manager, 2012

The majority of the experts ranked *Effluent Quality* as more important than *Sludge Quality*. The Provincial Decision Maker was the only expert in this study who ranked *Sludge Quality* as more important than *Effluent* during the pair-wise comparisons. He believed it was ultimately the most expensive and most problematic component of running a WWTP as no one wants it or knows what to do with it. In terms of *GHGs*, the Provincial Decision Maker, was conflicted with their scores. Though he gave the indicator a very low comparative score, they felt that GHGs were vital for the long-term sustainability. The Provincial Decision Maker was the only expert to connect the issue to the climate change debate. The Provincial Decision Maker, personally felt that more effort was needed in the part of *GHG*s. The problem, they explained, were the regulations for wastewater, “which don’t factor in things like GHG” (PD, 2012). Therefore even though the Provincial Decision Maker had different personal preference, when reviewing the performance of a WWTP, *GHG*s were not prioritized.

The Academic Consultant, similarly to the other experts, expressed the importance of fulfilling regulatory standards. The Academic Consultant acknowledged the national standard for *Effluent Quality*. He also reflected that GHG emission standards were very vague for wastewater treatment plants.

For the indicator *Revenue* from the criterion *Economic*, the experts generally did not see a value in WWTP *Revenues*. Interview results from discussions on *Economic* indicators together with those of *Environmental* indicators showed clearer distinctions between different types of *Revenue*. The experts did not seem to have experiences with the resale of effluent as a viable resource management option. Muga and Mihelcic (2008) explain that the quality of effluent is an important indicator for understanding the effluent reuse *potential*.

The Operations Supervisor, Municipal Manager and Provincial Decision Maker were all not asked specifically about water reuse. They discussed sludge sales, energy sales and energy self sufficiency when *Revenue* and the *Environmental* indicators were focused on. None of them saw the reused *GHGs,* or high *Sludge Quality* as particularly useful *Revenue* sources.

When water sale as a source of *Revenue* was mentioned during the interview the Provincial Consultant, they said, “Well, I haven’t really seen anything with water sale”, and continued with the explanation about current developments with sludge and biogas.

The Academic Consultant mentioned water reuse alongside energy and sludge sales in terms of potential *Revenue*. He mentioned water reuse standards and the needs of re-education of the public. The Academic Consultant also explained the fact that WWTPs were not designed to remove pharmaceuticals was a significant hindrance to reclaimed water sales. Though BC has established water reuse standards, and some locations are making use of the effluent, the high inexpensive water supply in British Columbia is probably a significant factor in reducing the reuse of reclaimed water. In Canada, it is expected that the interest in reuse will increase as water conflicts increase (Schaefer, 2004). It has been predicted that the lower mainland of British Columbia will experience a shortage of potable water in the next 50 years (Morales and Öberg, 2012). Additionally, it will be come a more attractive option when focus is directed towards the opportunities water reuse allows for saving on water *supply* infrastructure. As seen in many large municipalities, in the respective locations of the experts from this study, the water supply and wastewater sectors were separate from one another, in policy and in municipal level commissions (City of Victoria, 2011; MV-SS, 2012; MV-WWTP, 2012; Morales and Öberg, 2012). This potentially contributed to the lack of concern about water supply and or the future of water supply, and instead created a focus on output into the environment.

There were large variations in score among the experts for the indicator *Effluent.* Unlike the case of the *Initial* and *Long Term Costs*, the interviews revealed that a different ranking of *Effluent* did not necessarily mean that the participants thought of the indicator as considerably more or less important. Instead it reflected more on the relative ranking of the other indicators.

All experts stressed that *Effluent Quality* was a very important indicator as it was required for fulfilling the needs of permits as well as set regulations. None of them mentioned the possibility of using effluent as a future source of non-potable or potable water for their respective municipalities.

3.1.3 Social Indicators

The interviews revealed that the five experts found it difficult to integrate the *Social* indicators into the sustainability scheme, and into the understanding of a wastewater treatment plant. The Provincial Consultant specifically mentioned that they would have preferred *Social* criterion to have clearer measurements for their indicators. It has been expressed in the literature that social and cultural indicators are generally difficult to quantify, and few papers offer specific measures of these components (Balkema et al., 2002).

Aesthetics has been used as an indicator in a number of studies (Berndsson and Jinno, 2006; Muga and Mihelcic, 2008). In each piece of literature, the indicator was expressed in slightly different ways with varying subcomponents. Sometimes indicators, associated with *Aesthetics* were used separately in literature and public documents. For this study *Aesthetics* was used to signify odor, construction and visual appeal, as they are commonly used components.

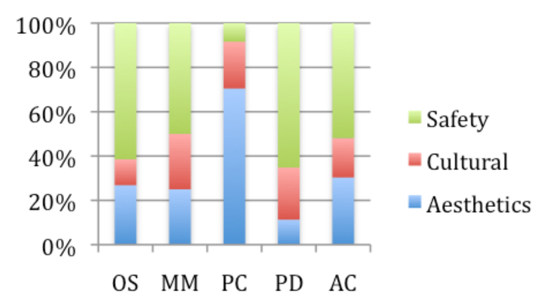


Figure 13 Expert Scores for Criteria Social - The scores of the indicators categorized under the criterion *Social* showed that the most contentious indicators in this set were *Safety* and *Aesthetics.* The Political Consultant had the most varied score in comparison to the other participants

In this study, the *Social* indicator with the largest score variation was *Aesthetics*. Most of the experts expressed that *Aesthetics* was comparatively much less important than *Perceived Safety*. This was shown through the ranking exercise as well as the explanations given during the survey. The Provincial Consultant allocated almost 70% of the weight to *Aesthetics* and less than 10 % to *Safety* (*Figure 13)*.

The Provincial Consultant expressed that the *Aesthetic* components, smell, disturbances and visuals, of the WWTP, were the most important. He felt that the smell and visuals of a WWTP could be improved and changed where necessary and so should be the major focus of the *Social* indicators. In terms of *Aesthetics*, the Operations Supervisor expressed that a WWTP is "not a park". This was reflected in the pair-wise comparisons as the Operations Supervisor gave *Aesthetics* a low score. For him it was not the least important indicator in the indicator set. The Operations Supervisor was, conflicted in terms of the components of the term. He did not believe visuals were particularly important, but odor complaints from the public were treated "very, very seriously".

The Municipal Manager verbalized the most concern with *Aesthetic*, and was also an advocate of visually appealing sites. The Municipal Manager often mentioned the public and their needs and preferences. Smell and visibility can have a large influence on the economics of a WWTP as people may demand changes. In terms of their own work, the Municipal Manager said, "Everything we do is driven by taxes". This suggests that they were very conscious that all their projects were funded by the public and so must also be pleasing to the public. Similar to the Operations Consultant, the Municipal Manager found that the issue of primary importance was to make sure there were "few odor complaints".

The Provincial Decision Maker believed that thought *Aesthetic* issues might exist they could be easily resolved, and so were a minor concern. This is opposite to the ranking of the Provincial Consultant. He explained that, "It's important for people to be comfortable with it [the WWTP]." At the same time the Provincial Consultant expressed that there were some risks in relying too much on comfort, because then you might "neglect the scientific rational". If the technology works and it protects the environment and people's health, responding to all of the public's requests may have a negative impact for the public.

Safety was prominent in the mind of the Provincial Consultant and was mentioned repeatedly. His focus, however, was on scientifically proven safety rather than *Perceived Safet*y, which was under the *Social* criterion. There was a verbal understanding and commitment to the needs and the importance of a "social contract". The Provincial Consultant explained that "outreach" and communication with the public were important for a project to work. He also expressed that society could potentially be "irrational". Therefore, the Provincial Consultant felt that a reliance on the public and a focus on pleasing the public could be a "danger" to the decision-making process. The Provincial Consultant believed if the guidelines were followed, people and the environment would be protected. If a WWTP fulfilled the guidelines, the potential negative perspectives expressed by society should not halt projects. It was considered normal for people to react negatively to being close to wastewater treatment plants. The Provincial Consultant explained their low scores from their ranking exercise as resulting from their belief that the public already perceived wastewater treatment plants to be safe. Therefore, *Perceived Safety* was not a component of concern.

With a focus on the public and on the employees of the WWTP, the Operations Supervisor believed that *Perceived Safety* was of primary concern. The Operations Supervisor, as the Municipal Manager showed little distinction between their thoughts on *Perceived Safety* and actual technological safety. Additionally both experts expressed the safety of a WWTP as the security of people who work and visit a facility. The Municipal Manager expressed a particular concern that workers and public visitors need to be safe due to the "liability of the buildings".

The Operations Consultant thought of the WWTP staff, facility visitors as well as people living close to the WWTP when considering *Safety.* The Provincial Consultant only thought about *Safety* as an issue of people living close to wastewater treatment plants and the Provincial Decision Maker spoke about *Safety* as it connected to those whose sewers lead to the hypothetical WWTPs in question. The Provincial Consultant spoke about communities in general with particular references to First Nations groups.

Cultural Acceptance was the indicator with the overall lowest score for the indicators in selected for this study (*Table 1*). Some of the experts thought that *Cultural Acceptance*, should be merged with other indicators or removed from the objectives hierarchy due to its relative irrelevance to wastewater matters.

The majority of the experts believed that society overall would not be positive about its proximity to wastewater.

"…Nobody really likes having wastewater treatment plants…"

Operations Supervisor, 2012

The Municipal Manager expressed the connection he believed existed between *Aesthetics* and *Cultural Acceptance*.

"… it's the same… You know if it's aesthetically pleasing then its accepted, that's how I see it".

Municipal Manager, 2012

The Provincial Consultant expressed another connection. They thought that *Perceived Safety* and *Cultural Acceptance* were the related indicators. The Provincial Consultant stated that projects could not afford to ignore C*ultural Acceptance.* Projects needed a "buy in" from the public in order to be successful.

The Academic Consultant expressed a first hand experience the importance of the cultural component in WWTP selection. He expressed different international and local cultures, which had specific needs from treatment systems. However, the Academic Consultant said that "as an engineer" he did not know the details of how many different cultures handle human excrement. Though, overall, the experts spend little time discussing cultural issues, distinctions between different cultural and religious groups have been identified through various national and international research projects (Ellis and Tang, 1991; Mead et al., 2007; Mallett, 2007). Various cultural taboos connected with human waste have the potential to influence the prioritization between techniques (Ellis and Tang, 1991; Mallett, 2007). Additionally, the UN's *Agenda 21* (1992) expressed that an integral part of sustainable development was the inclusion of minority ideals in decision-making.

For the indicators categorized under the criteria *Social*, the participants primarily had very similar scores (*see Figure 13*). Only the Provincial Consultant expressed a low priority to the *Perceived Safety* of society, and gave a very high score to the comfort felt through a high *Aesthetic* performance. The verbalization of the thoughts of the participants through the interview showed interesting variations. Though the scores of *Aesthetics* were very similar with all four of the experts, they expressed different experiences with the indicator. They also all had a feeling that it was typical to have a constant "NIMBY-ism" (PC, 2012) or push back from society.

3.1.4 Technical Indicators

The *Technical* indicators, showed the least verbal contradictions or variations in ranked importance. This could potentially be contributed to the fact that four of the five experts were engineers, making the technical/engineering knowledge best understood with the least potential for disagreements (*see Figure 14*).

Most scores for the criterion *Technical* were of given similar weights among the different experts, however, the Operational Supervisor had the highest difference in score between the experts for the indicator *Simplicity* (*Figure 14).* This is believed to have come from the experiences of actually working on-site at WWTPs. Through the day-to-day workings the Operations Supervisor recognized that *Simplicity* is required for the functionality of the technology. The Operations Supervisor expressed that “if its too complicated people won’t do it” (OS, 2012). The other four participants had low scores for *Simplicity* due to a general feeling that people could always be trained to work with new or different technologies. It was not seen as an issue of concern. As the Municipal Manager expressed it, the “bar could always be set higher”. A similar result for *Simplicity* was seen in the results of Singhirrunnusorn and Stenstrom (2009). They described practitioners involved in the hands-on operation of a WWTP showing higher preferences towards the indicator S*implicity* than other stakeholders. Though it has been expressed that simple technologies are particularly preferred in the developing world (Singhirrunnusorn and Stenstrom, 2009), studies in the USA have also expressed that complex machinery led to low controller understanding and limited treatment plant performance (Muga and Michelcic, 2008 pp)

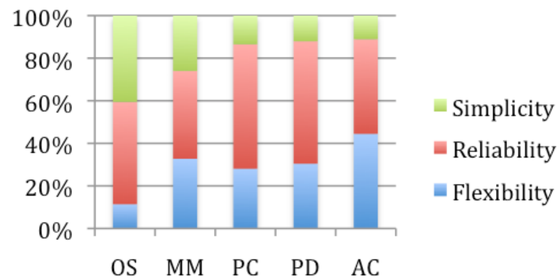


Figure 14 Expert Scores for Technical - Four of the experts had very similar scores for the *Technical* criterion, the most variation came from the scores of the Operations Supervisor

Flexibility to adjust to future needs was given a lower weight by the Operations Supervisor than by the other experts (*see Figure 14*). He explained that *Flexibility* was generally a concern of “other departments” and as considering the future performance of the WWTP it was not central to its immediate management. The Academic Consultant explained that few WWTPs were built with *Flexibility* in mind because after about 30 years a system would require a complete overhaul.

Similarly to the other participants Academic Consultant thought that *Reliability* was important for the success of a WWTP. There was a general preference for the *Reliability* of a wastewater treatment plant over the other two indicators. This was clearly expressed by the Municipal Manager, who said,

"…these systems… run 24/7.. Christmas and the middle of the night, so if they are not reliable it requires a lot of staff to supervise…"

Though the experts believed *Reliability* was the most important *Technical* indicator, there was also an agreement among them that they were not worried about the *Reliability* of WWTPs. All the participants had trust in the abilities and functionality of the technologies existing for wastewater treatment. The Academic Consultant had not experienced any WWTP in BC ever really failing.

"Technologies didn't fail, the technology worked, the technology is robust, so reliability is not an issue… "

Academic Consultant, 2012

The Operations Supervisor clarified that most components of wastewater treatment plants have redundant pieces that can be implemented if there is a problem, or if there is maintenance taking place.

3.2 Ranking of the Alternatives by the Academic Consultant

The Academic Consultant scored the alternatives according to how he perceived their performance on the thirteen indicators. These scores led to a prioritization of the wastewater treatment alternatives. The Academic Consultant prioritized the sequencing batch reactor (SBR) highly over the other three alternatives for the *Initial Costs* and *Long Term Costs.* BAF was seen as the highest performing alternative in terms of its *Sludge Quality* and *Aesthetics.* SBR was prioritized for *GHG* and *Simplicity* however, BAF was believed to have similar performances for the indicators.

The Academic Consultant expressed through their ranking that the wastewater treatment alternatives performed to the same level for the indicators *Revenue*, *Perceived Safety*, and *Reliability*. Below, in section 3.3., details are given on the ranking of the alternatives for the four indicators, *Initial Costs*, *Long Term Costs, Effluent Quality* and *Aesthetics*.

3.3 The Overall Preferred Technology

The aggregated average weights of the five experts for each of the 13 indicators combined with performance scores of the alternatives led to the identification of Sequencing Batch Reactor (SBR) as the overall most preferred technology for fulfilling the sustainability objectives presented in this study. The alternatives each had components, which made them preferable from different perspectives. The overall ranking showed a comparatively small range in scores (7 points) (*see Figure 26*). As weights are based on subjective judgments, a sensitivity analysis allows for an understanding of the stability of the ranking with varying conditions (Dabaghian et al., 2008; Bottero et al., 2011).

The flowing sensitivity analysis was done for the indicators *Initial Costs, Long Term Costs, Effluent Quality* and *Aesthetics*. First, the ranking of the alternative technologies are shown for their comparative performance on each of the four indicators. Then the scores of the technologies elicited from the Academic Consultant are presented with their overall performance on the indicator set, with the average importance ranking of each indicator. Thereafter, the scores of the indicators were given both the highest and lowest weights within their indicator sets, and their scores are shown. This displays to what extent the indicators selected contribute to the final overall preference scores of the alternatives.

3.3.1 Sensitivity Analysis for Initial Costs and Long Term Costs

Differences were found between the alternatives and their performance on the indicators. From an economic perspective, the Sequencing Batch Reactor (SBR) was the highest performing alternative in terms of its performance on *Initial* and *Long Term Costs (Figure 15 and Figure 16).* The BAF was the second most preferred technology, while VSBR and MBR received similar scores. These scores suggested that the Academic Consultant believed that the alternatives were of similar relative cost both for their implementation and for their operation and maintenance.

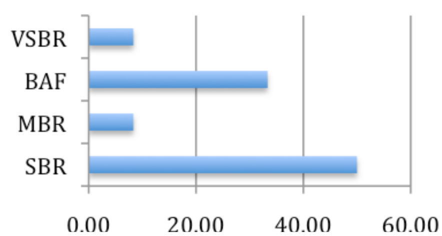


Figure 15   Ranking of Alternatives for *Initial Costs* - SBR was the technology, which had the most preferred performance in terms of the Academic Consultant, suggesting a preference for low cost technologies

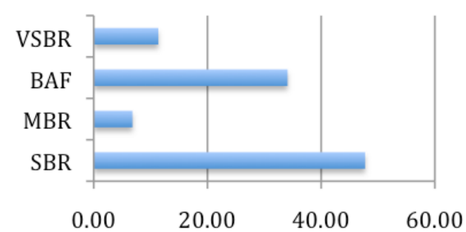


Figure 16   Ranking of Alternatives for *Long term costs* allocated by the Academic Consultant - SBR was the technology with the most preferred performance, so it was the least expensive even on a 50-year time frame

T

his difference in performance among the alternatives could also be seen in the sensitivity analysis. The geometric mean of the scores of all of the participants showed that overall *Initial* and *Long Term Costs* had a higher weight than *Revenue (Table 1)*. SBR is the least expensive alternative, and consequently was the highest performing technology for the criteria *Economic*.

As the costs were considered important, SBR stands out as the strongest performing wastewater treatment alternative, followed by the Biological Aeration Filter (BAF) (*Figure 17*).

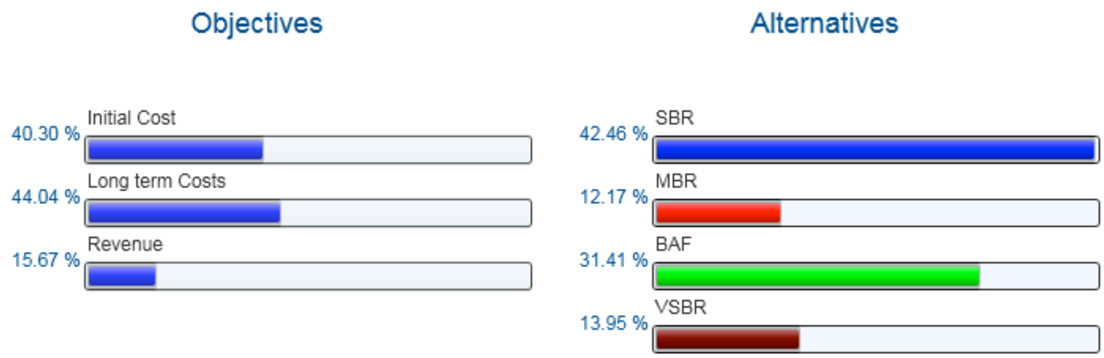


Figure 17 The Performance of the Four Alternatives for Economic - Here the performance of the four alternative wastewater treatment technologies can be seen according to the mean indicator scores of all of the participants, under the criterion *Economic,* the overall average score of Initial costs and Long Term costs are similar, with Revenue having the lowest overall score. Due to this ranking the Sequencing Batch Reactor is the highest performing technology

After the aggregate scores were found, the sensitivity analysis was implemented. Both *Initial Cost* and *Long Term Costs* were given a highest and lowest ranking within their criteria grouping (*Economic*) and an influence was seen on the preference of the alternatives (*Figure 18 and Figure 19)*. Though the participants were considerate of the different sustainability components of this study in their ranking, the costs of the WWTP continued to be prominent in their minds. This is common with decision-makers of public infrastructure, as it is primarily understood that there is little profit to be made or expected (Brunner and Starkl, 2004; Vanier, 2006; Dabaghian et al., 2008; Muga and Mihelcic, 2008: Fidelis, 2011).

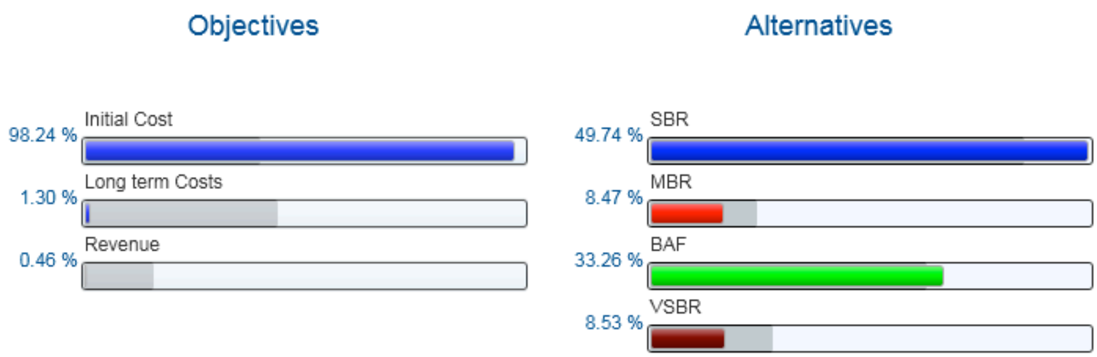


Figure 18 Sensitivity Analysis for *Initial costs* - Here the weight of *Initial cost* is increased, and the other two indicators are made insignificant, in response SBR becomes even more prominent. The shift in priorities are minor, indicating the importance of *Initial Cost* within this indicator set

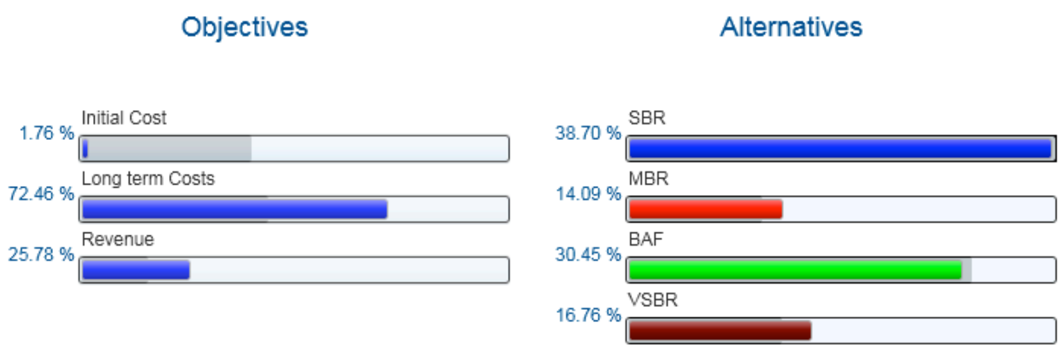


Figure 19 Sensitivity Analysis for *Initial costs* - When the weight of *Initial costs* decreases, SBR is still the most prominent technology. This is because when *Initial Costs* has a low importance, the *Long Term costs* become more prominent. SBR was also the highest performer in terms of its *Long term costs*

The SBR has the lowest set up and implementation costs, and the Membrane Bioreactor (MBR) and Vertical Deep Shaft Bioreactor (VSBR) are the most expensive technologies (*Figure 18* and *19*). When the *Initial Cost* weights vary, the SBR continues to be prominent. When *Initial Costs* have a low weight, the weight of *Long Term Costs* increases, and SBR is still the top performer. This identifies SBR as the least expensive in terms of its operations and maintenance costs. SBR is a simple secondary treatment process, which works through tank storage and a mixed liquor aeration system (Metcalf and Eddy, 2003) (*Figure 15* and *16*). BAF and VSBR require intensive, difficult and expensive construction and supervision due to their underground storage (Wang et al., 2009).

3.3.2 Sensitivity Analysis for Effluent Quality

All the wastewater treatment alternatives selected for this study are able to be set up to produce effluent up to CCME (2009) standards. The MBR system, however, is a tertiary treatment system (*Figure 20)* involved in water refinement and thus it produces effluent of considerably higher quality than the other systems (Metcalf and Eddy, 2003; Ng et al., 2007).

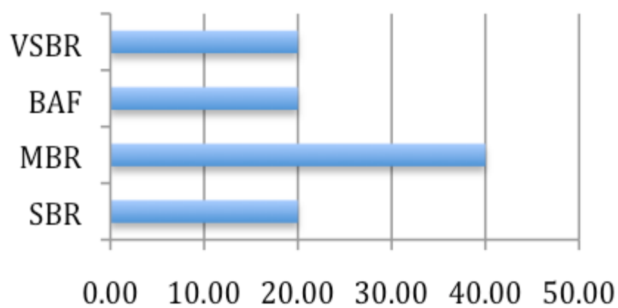


Figure 20 Ranking of Alternatives for Indicator *Effluent Quality* – The ranking of the alternatives based on their comparative performance for *Effluent quality.* MBR was the technology with the most preferred performance, so it produced the highest quality wastewater

The overall scores show that BAF was the highest performing technology for the criterion *Environmental*. Though *Effluent* was the highest ranked indicator, *Sludge* had a near equal importance in terms of fulfilling the criterion. Therefore, BAF's high performance on *Sludge Quality* increased its ranking (*Figure 21*). When *Effluent* was given the lowest possible weight, *Sludge Quality* became the most prominent indicator under the criterion *Environmental (Figure 21)*. The distinction among the different alternatives increased. BAF and SBR became the wastewater treatment technologies with the preferred performance, due to the high quality of sludge provided through their processes (Metcalf and Eddy, 2003). This also expresses that MBR is not a leader in its performance for the other three indicators categorized under the criterion *Economic*.

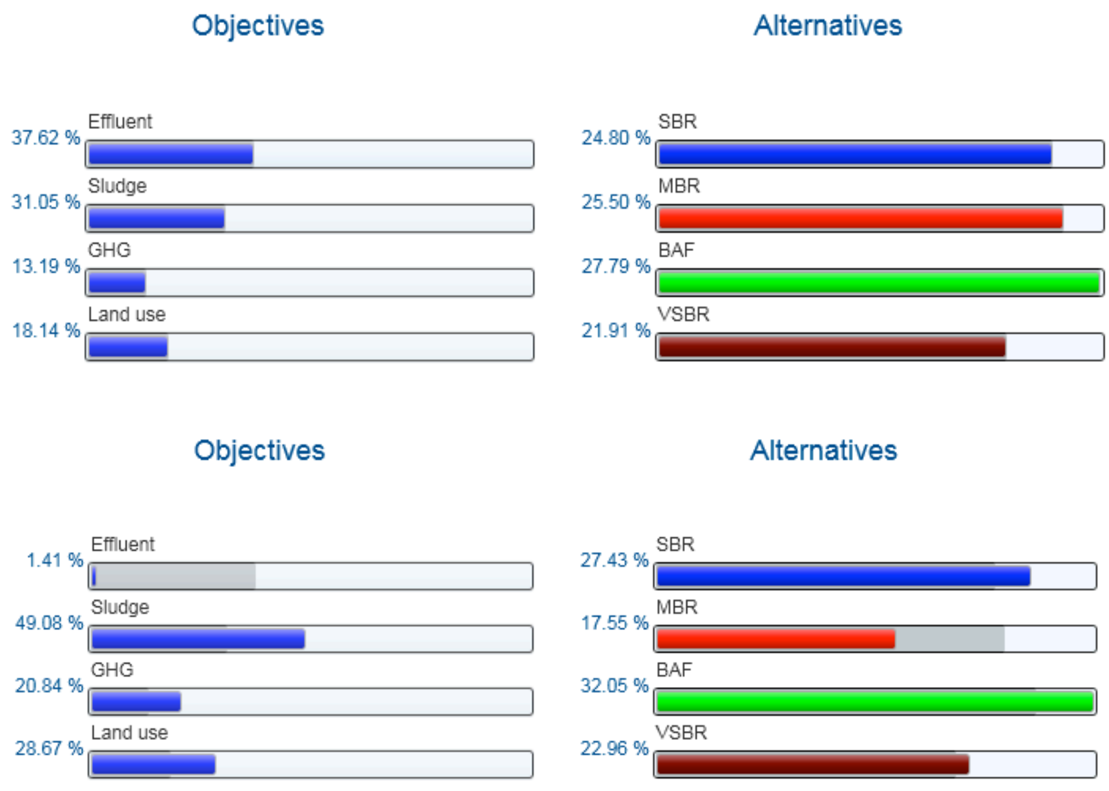


Figure 21 Sensitivity Analysis for Effluent - When the weight of *Effluent* is lowered, the importance of *Sludge* becomes prominent and MBR has a decrease in its ranking

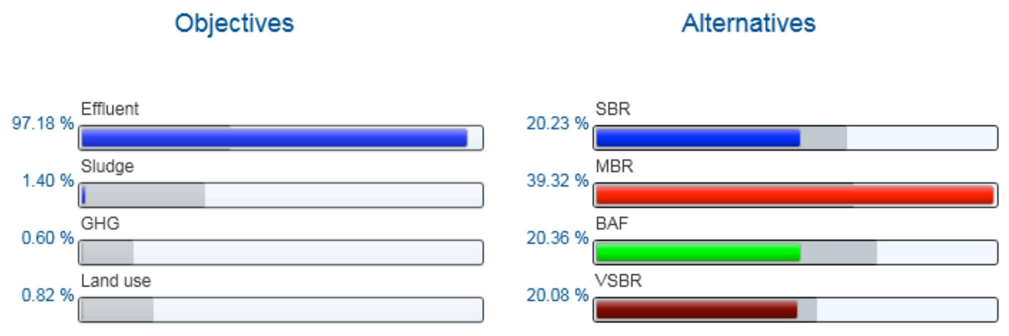


Figure 22 Sensitivity Analysis for *Effluent* - When *Effluent Quality* was given the highest weight, MBR became the most evidently prominent technology

When *Effluent Quality* was given the highest weighting, MBR became the preferred technology *(Figure 22)*. Unlike the other three technologies, MBR is a tertiary treatment process and it produces effluent of BOD and TSS< 10 ppm. It is also able to effectively process high or unexpected nutrient loads (Arora et al., 1985).

3.3.3 Sensitivity Analysis for the Indicator Aesthetics

In terms of the indicator *Aesthetics,* BAF was considered to be the comparatively best performing alternative according to the scores given by the Academic Consultant *(Figure 23).*

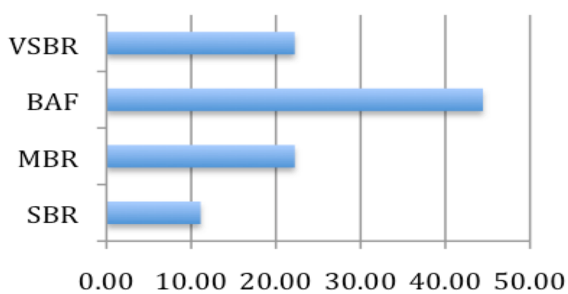


Figure 23 Ranking of Alternatives for Indicator *Aesthetics* - The ranking of the alternatives based on their comparative performance for *Aesthetics.* BAF was the technology with the most preferred performance, so comparatively it is believed to have the negative visual and odor influences on society

The performance of BAF for the criterion *Social* can also be recognized through the sensitivity analysis. With the overall combinations of scores of the criterion, *Social* and the combined high weight of *Safety,* MBR is the 'leading' alternative. The mean scores of the participants for the indicators ranking under the criterion *Social* showed that *Safety* was overall thought to be the most important indicator (*see Figure 24*). *Aesthetics* and *Acceptance* received similar overall scores.

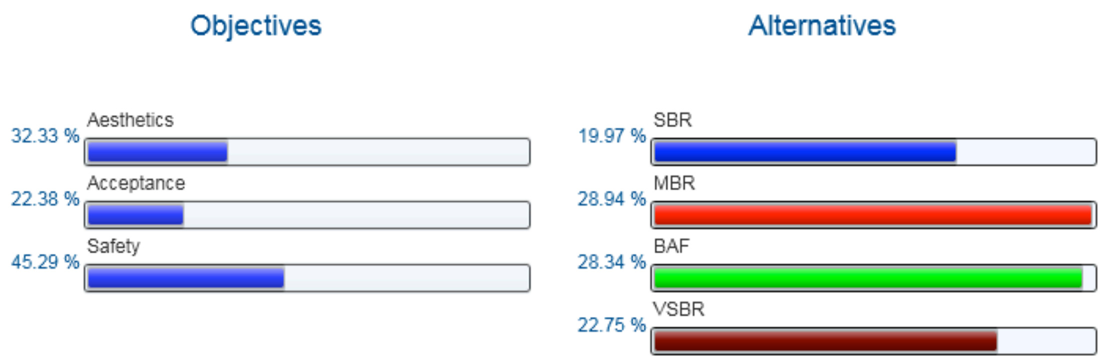


Figure 24 Performance of Alternatives for Criterion *Social* - Mean scores of the five participants, showed that the MBR and BAF had almost the same performance. MBR, however, was the highest ranked alternative

The manipulation of the weight of *Aesthetics* influenced the most preferred technology. When *Aesthetics* was given a very low weight, *Safety* remained the most important indicator, and *Cultural Acceptance* increased its prominence (*Figure 25*). MBR continued as the highest ranked technology. Its prominence became clearer as it had the highest score for *Cultural Acceptance.* The Academic Consultant noted that various First Nations societies have often preferred the MBR technology. Additionally, the high quality effluent produced by MBR may also influence the *Safety* indicator (Ahn et al., 1999).

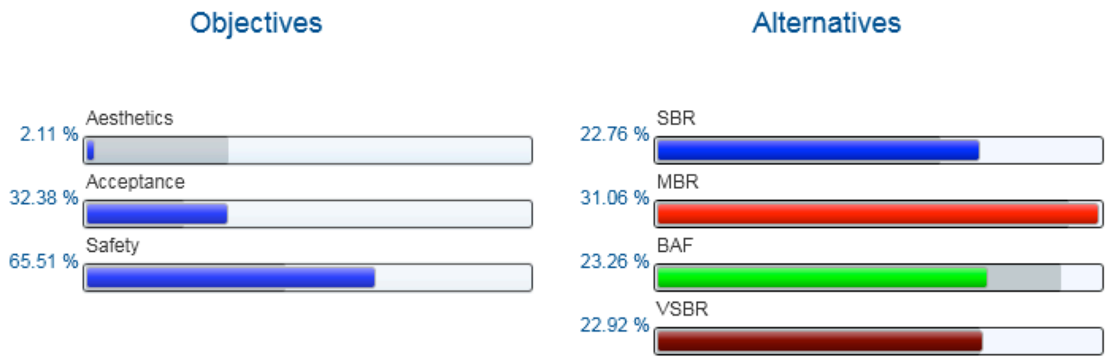


Figure 25 Sensitivity Analysis for *Aesthetics* - When the weight of Aesthetics was decreased in relation to the other two indicators groups under *Social*, *Safety* became prominent, and MBR stood out as the most preferred technology

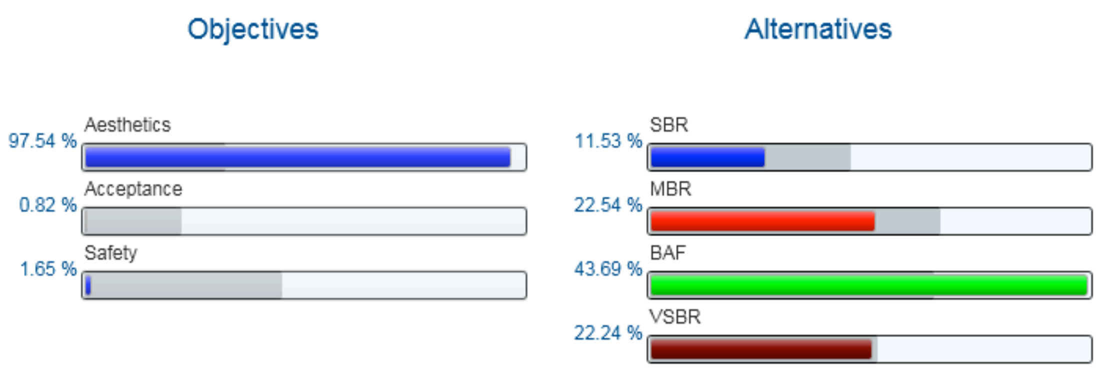


Figure 26 Sensitivity Analysis for *Aesthetics* - *Aesthetics* was the most contentious indicators, but overall it was considered one of the least important, nonetheless, when it's weight was increased in comparison to *Cultural Acceptance* and *Safety*, BAF over took the other three alternatives in terms of the preference of its performance

When *Aesthetics* was manipulated to be the most important component, BAF became the clear dominant technology (*Figure 2*6). For this criterion, MBR was the overall preferred alterative, for this indicator set; however, due to its low performance on *Aesthetics*, it was not the robust leading technology. BAF can be stored underground and so it has a smaller footprint, and less visual impact than the other technologies. Though the VSBR technology on its own, only takes up 20% of conventional technologies (USEPA, 1982), VSBR requires pre and post-treatment, which take up more space. BAF requires no post-treatment.

The performance of the technologies had large variations for the indicators, *Initial* and *Long Term Costs, Effluent* and *Sludge Quality* and *Aesthetics.* The sensitivity analysis showed that the indicators that elicited opposing scores from experts, could potentially have a large influence on the preferred technology. Sensitivity analyses allow a researcher to understand if the final score is stable with different inputs when the scores are changed. The analyses also show how the changes in indicator scores influence the order of preference of the alternatives. As judgments by the participants are subjective, it is important to see if a technology can withstand the test of other indicator preferences. Changes in the indicator scores lead to observed changes in the ranking of the alternatives, as well as altering the order of their preference.

The sensitivity analysis shows that SBR is only robust as the leading technology for the *Economic* criteria *(see Figure 27)* as it has the highest performance for *Initial* and *Long Term Costs.* Otherwise the performance of the SBR varies from most preferred to least preferred for the other criteria, and it changes with differences to the weights of the indicators. BAF was assessed as the highest performing technology for the *Environmental* indicators, and MBR was the highest perceived performer for the *Social* indicators. BAF has the most preferable performance in terms of the *Aesthetics* of the facility and the quality of its *Sludge* and MBR is able to produce the highest quality *Effluent*.

The Analytic Hierarchy Process was used to aggregate the all the scores. Combining the overall average scores of the indicators and criteria, along with the scores of the alternatives, led to the overall most preferred wastewater treatment technology. For this study, the SBR, was seen as the ‘most sustainable’ wastewater treatment alternative (*see Figure 29*). This seemed to be particularly connected to the high performance of SBR for the *Economic* criterion, as well as the general agreement on the importance of that criterion by the five participants. The graph below summarizes the performance of each of the alternatives for the set of indicators categorized under each criterion as shown in the sensitivity analysis. It also shows the average scores of all the five experts in terms of how important they believed the criteria were for fulfilling the overall goal of 'most sustainable wastewater treatment plant'. On the right side of the graph, 'overall' indicates the total ranking of the technologies, after their scoring on each of the indicators, was combined with the average importance of the criterion (see *Figure 27* and *Figure 28*). Though SBR outperformed the other alternatives for its performance on *Economic* indicators, overall the criterion *Economic* was not seen as the most important of the four, influencing the amount that SBR outperformed the other alternatives.

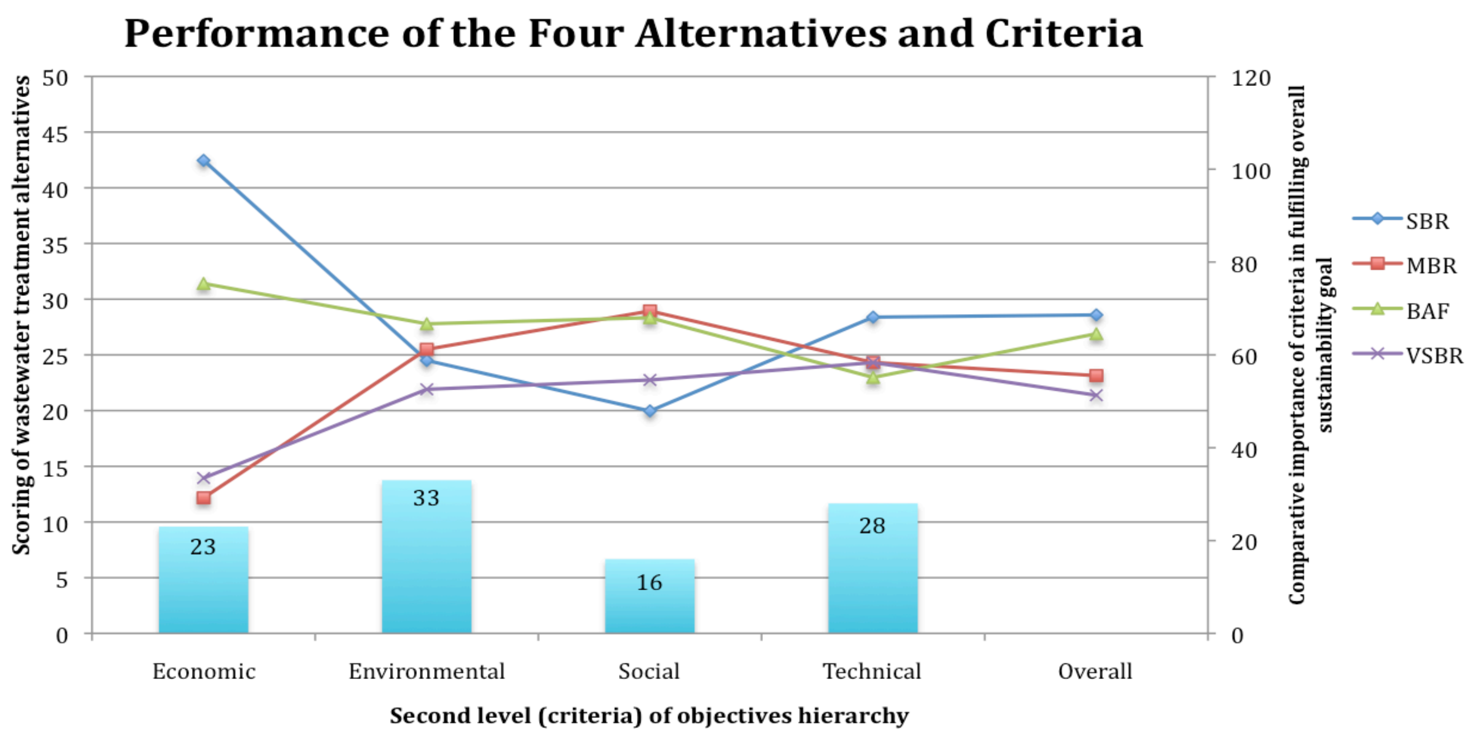


Figure 27 Overall Performance of Alternatives - This performance graph shows the results of this AHP study and shows how the alternatives perform according to the criteria and the overall goal

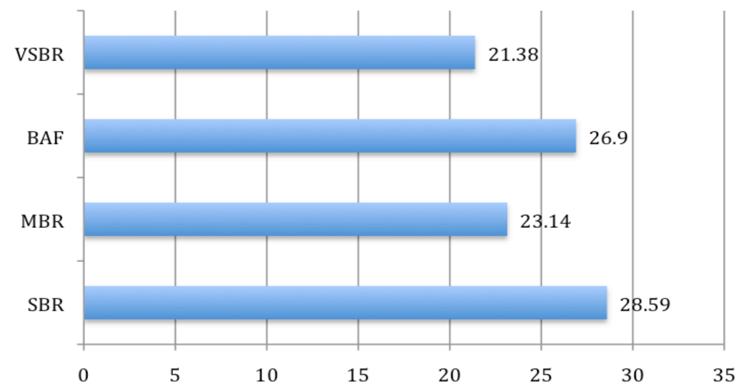


Figure 28 The Overall Ranking of the Alternatives - The bar graph is another display of the 'Overall' scores shown in Figure 27. SBR is the most preferred technology overall and VSBR is the least preferred overall

3.4 Sources of Contention and Their Influence on the Separate Expert Scores

The responses of the wastewater experts were reviewed in order to understand what issues explained the different scores for the indicators selected for this wastewater treatment selection study. From the interviews, it seems that the perspectives were influenced largely by their work experiences and the day-to-day complications they have confronted. It seemed that the different experts subconsciously created their own hierarchies while completing the ranking exercises. The Municipal Manager believed that the *Technical* criterion overarched the other three, and the Provincial Consultant and Academic Consultant believed that all indicators could potentially be sub-grouped under *Economic*. This reorganization of the hierarchy influenced how they ranked and thought about the different indicators. The experts allocated the highest score to the criterion, which they believed should have been the overarching super-category of the other criteria. Additionally, some of the indicators were described as being connected or almost the same thing. Though the indicators were selected on their independence from each other, it is impossible to completely disconnect their associations. It suggests the need for a method that allows a measurement to understand the connections participants see among the components of the objectives hierarchy.

The different interpretation of the objectives hierarchy seemed to come from the fact that there was no standard definition or guideline set up for wastewater treatment plants and their contributions to local sustainability goals. Literature and different public documents all approach the topic in slightly different ways with different measures without a clear single set of definitions for the wastewater field. Pahl-Wostl et al. (2011) recognized that differences in mental models are “key reasons” for difficulties in communication and coming to agreements (pp 853).

There also seemed to be a particular interest in regulations that exist for the performance of wastewater treatment plants. Four of the five experts expressed the feeling that the technology must conform to the regulations put into place by the government. They generally believed if the guidelines were followed, people and the environment would be protected thus leading to sustainability. The Academic Consultant, on the other hand, believed that technologies should aim to *exceed* the laws and challenge the status quo. Performing beyond what was required or expected would have the ability to influence perspectives of the public as well as encourage government decision-making for sustainability.

There was a different understanding of budgeting needs and the limits of over-budgeting. The Provincial Consultant and Academic Consultant believed that *Initial Costs* should be as inexpensive as possible. These two experts also ended up selecting *Economic* as the most important criterion of the study. The Provincial Decision Maker and Operations Supervisor were adamant that high, smooth functioning systems should be established regardless of the initial costs. The Operations Supervisor, as well as the Provincial Decision Maker, thought that over-budgeting in the present would save money in the future with a reduction of breakages and repair. Overall they believed that the criterion *Economic* was the least important of the four criteria. The Operations Supervisor and the Provincial Decision Maker believed it made the most sense to decrease long-term costs, however, they also did not think that the cost/benefit analysis should focus on the monetary value. As it was a piece of public infrastructure, its goal should be protecting the environment and the people, regardless of the cost or the financial returns.

Among the participants there also seemed to be variations in how they saw the public and how they distinguished between societal groups. One expert explained when constructing wastewater infrastructure, it was important to consider the wealth of the neighboring community.

"…affluent neighborhoods where people tend to be very vocal and people may have some pull with counsel, and they say well we really don't like this so you need to change the positioning…."

Another expert expressed that different cultural beliefs can lead to considerable changes in technological needs. The other three experts primarily saw 'the public' as one large group, undistinguished in terms of their reaction to wastewater treatment plants. The experts used the term NIMBY (Not In My Back-Yard), to encompass feelings of the public. The population needs wastewater treatment plants, but no one wants to see them or to live close to them. NIMBY is also the most common way the public is referenced in the literature (Metcalf and Eddy, 2003; Tuzkaya et al., 2008; Bottero et al., 2012). The understanding of who the public was also seemed to be distinguished by those living in the proximity of WWTP and the people who directly interacted with the facility itself. Though society was believed to be important by all the participants, the criterion *Social* was given varying scores due to the lack of regulations and easy measurability of the components. Looking at the scoring of the criteria of each of the participants supports the understanding of the conflicting perspectives, not only on the indicator level but also on the criteria level (*see Figure 29*).

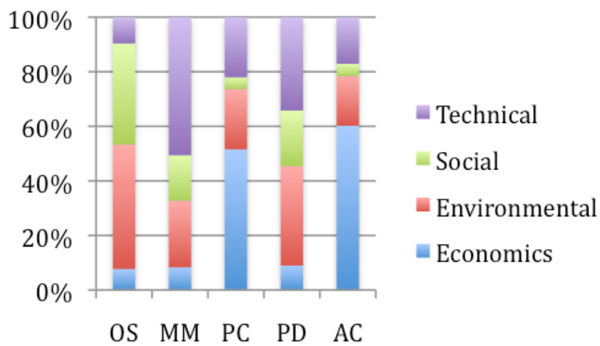


Figure 29 The Criteria Scores - The participants had varying scores in terms of the relative importance they believed each of the criteria had in fulfilling the overall goal of the study

SBR was found to be the ‘most sustainable’ wastewater treatment alternative, overall for this study as described in section 3.3. The preference ranking of the alternatives was also reviewed according to the indicator and criteria scores for each of the separate wastewater experts. The aggregated scores from four of the five participants led to the prioritization of the SBR as the ‘most sustainable’ wastewater treatment alternative for this study. This was despite the differences in expressed opinions and scores from the pair-wise comparisons. These same four participants also had the same preference ranking of the alternatives. Though the end scores of the technologies themselves varied, for the experts of the study, the prioritization was the same. SBR was the most preferred followed by BAF. Then MBR and VSBR were the least preferred (*see Figure 30).*

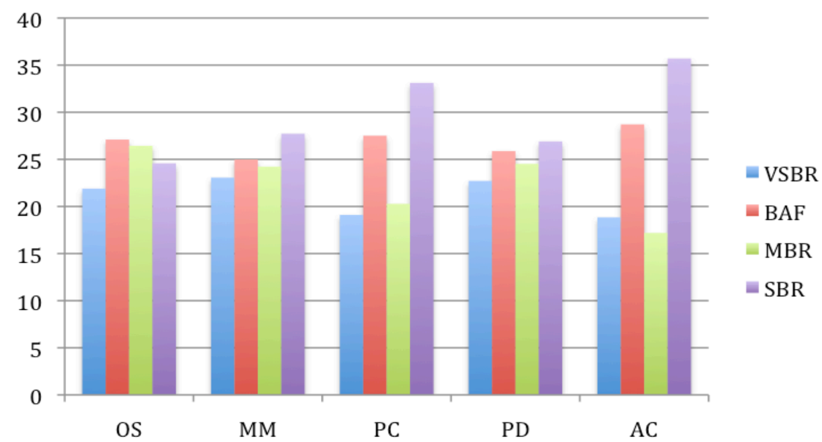


Figure 30 Ranking of the Alternatives Using Expert Scores - The prioritization of the alternatives by each of the experts can be seen here. SBR (purple bar) is the most preferred alterative for four of the participants

SBR was the highest-performing alternative, due to the high importance, given by each of the four experts, to either the *Economic* indicators as well as the *Technical* indicators. SBR was the highest performing technology for the indicators categorized under both of these criteria. The Operations Supervisor had the largest difference in their end preferences. BAF was ranked the 'most sustainable' wastewater treatment alternative according to the interests of the Operations Supervisor (*Figure 31)*. MBR was the second most preferred technology. SBR alternatively was the third most preferred technology and VSBR continued to be the least preferred alternative. The major issue seemed to come from the fact that the Operations Supervisor showed a preference for the *Environmental* and *Social* indicators.

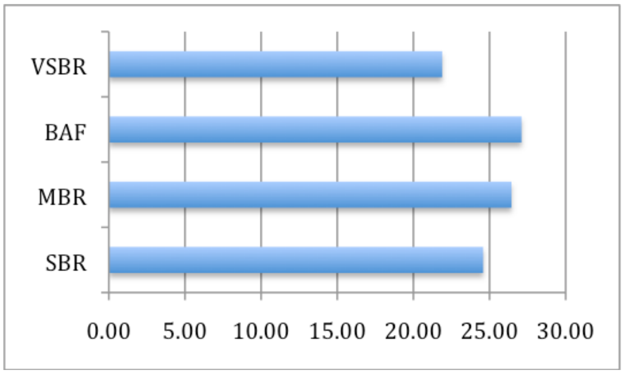


Figure 31 The Prioritization of the Wastewater Treatment Alternatives by the Operations Supervisor - They had similar weights, however BAF was the leading alternative

This review of the score variations of the separate experts showed the participant with scores, which conflicted with the final combined average scores in Figure 28. When averaged, the scores of the technology were relatively similar. Wastewater treatment selection is complex and it involves value distribution that requires insights from many different stakeholders. The consideration of different stakeholder values can improve the acceptability of the end technology selected. The results show that despite differences in preferences of the separate participants in the study, the end prioritization of alternatives still has the potential to be the same. In this case only the Operations Supervisor preferences would not be aligned with the selection using the average scores. This transparency allowed by the AHP process supports insights into how each individual participant and their scores contribute to the overall scoring. This has allows an analysis for the details of the differences among participants, as well as which criteria and which indicators were the most prominent for the final scores.

Chapter 4: Conclusion

This chapter synthesizes the main insights gained through the separate and aggregate scores among the five experts. Though the ranking exercise elicited varied scores among all of the participants, the Sequencing Batch Reactor was found to be the overall most sustainable wastewater treatment alternative according to the indicators selected for this study and the opinions of the five experts. The limitations of the study include the setbacks of AHP. The lessons of the study are also used to suggest further developments to the objectives hierarchy to support future research on the topic. Through an example with five experts, this study shows that the selection of wastewater infrastructure may benefit from the integration of processes, which reveal what are generally implicit perspectives.

4.1 What was Researched

An objectives hierarchy was developed with four criteria and 13 indicators as sub-components of sustainability in the wastewater field. Four alternative wastewater treatment systems were selected for comparison. The study integrates theories on indicator selection with decision-modeling literature related to wastewater treatment. The results could help in the formulation of language and objectives to involve and connect experts from different stakeholder groups with different ideals.

Five wastewater experts gave their scores and opinions on the indicators and criteria of the constructed objectives hierarchy. One of the participants, the Academic Consultant, also ranked the alternatives for their performance on the selected indicators. This information was used to find the overall most important indicators, as well as the indicators with the highest variation in scores among the participants. The interviews helped gain a more detailed understanding of the differences among the experts. The rankings resulting from the pair-wise comparisons were also used to find the most preferred alternative for each of the separate participants. The mean of the participants' scores were used to indicate the overall prioritization of the wastewater treatment alternatives. A sensitivity analysis helped to understand the influence indicator scores could have on the ranking of the alternatives.

4.2 Considering the Opinions on Indicators and their Weights

This study of sustainability indicators for wastewater treatment selection showed that the most contentious indicators among those studied were *Initial Costs* and *Long Term Costs*, *Effluent Quality* and *Aesthetics*. None of the wastewater experts had the same scores for all the indicators and criteria. Different experiences lead to, at times, opposing views on the significance of the components of the objectives hierarchy. It was found that the proximity to the financial decision-making for the construction of a WWTP leads to an increased value for *Initial Costs*. According to the experts, it also seemed that the *Initial Costs* were more important from the perspective of the public.

Effluent Quality was considered a very important component of decision-making. This seemed to be firmly linked to the regulations and associated consequences of noncompliance in place for WWTPs. There was also a general agreement that the fulfillment of these regulations was part of fulfilling sustainability. Only one of the experts suggested the importance of performing beyond the *Effluent* regulations and fulfilling the needs of water reuse. There was little consideration from the other experts on supporting water supply through effluent reclamation.

Aesthetics was considered a relatively unimportant *Social* indicators for most of the participants, and was identified as one of the least important indicators overall. The problem with the group of *Social* indicators seemed to lie in its aggregation of different subcomponents. The participants were quite unified in the importance of reducing odor, and responding to the odor complaints of the public. There were, however, large variations in the way the participants described the importance of visual aesthetics. The Provincial Consultant ranked *Aesthetics* as the most important *Social* indicator. He expressed that it was possible to improve the *Aesthetics* of wastewater treatment plants, while the other components of *Perceived Safety* and *Cultural Acceptance* were not a major issue, as he understood the problem to be an implicit dislike of wastewater treatment plants that could not really be changed.

Among the five experts, there was a general agreement on the importance of *Reliability* in the performance of the wastewater treatment plant. At the same time there was a feeling of trust in technologies and their ability to perform. There was, however, a difference between the Operations Supervisor and the other four experts in terms of what they believed the employees of a WWTP were willing to do. This could be seen from the discussion of the indicator *Simplicity*, and the fact that the Operations Supervisor was the only one of the five to express concern with technologies being too complex.

4.3 The Sequencing Batch Reactor as the 'most sustainable' Solution

The results of this study showed that SBR was the preferred technology from overall average scores. Differences in importance scores for the indicators can influence the preference ranking of the alternatives of a study. Using the average weights of the indicators and criteria from the scores of all five participants led to the prioritization among the alternatives, with SBR being the highest ranked followed by BAF, MBR, and VSBR. The overall scores showed comparatively small ranges in the prioritization of the wastewater treatment alternatives. Regardless of the high variations among the indicators, the aggregated scores led to very similar prioritizations. The sensitivity analysis on the indicator level showed that SBR was only a stable 'leading' alternative for the *Economic* criterion. This resulted from its high score for both the *Initial* and *Long Term Costs*. For the *Environmental* and *Social* indicator sets, SBR was not identified as the preferred alternative, even when weights were varied significantly during the sensitivity analysis. This shows that SBR is stable in its lower prioritization for these indicator sets even with changes to the indicator weight. SBR varied in its performance from most to least alternative in terms of its performance for the four criteria, depending on its performance on the separate indicators. A review of the indicator level indicated that SBR was prominent for this criterion due to its performance on *Simplicity*.

A review of the separate scores of the experts was helpful here, because it showed, which one of the experts opinions were so different from the others that it changed their preferred technology. For this study each of the participants had varying scores for the majority of the indicators and criteria, however it was the Operations Supervisor who had variations in score, which lead to changes in the end preferred alternative. The other four participants had the same prioritization of the alternatives. This is useful because it shows that different perspectives can still lead to the similar preferences among a selection of technologies. It also helps to pinpoint which components of the objectives hierarchy had the largest influence on the end prioritization.

For this study it seemed that the preference for the *Environmental* and *Social* indicators, as well as the low interest in the *Economic* indicators led to the varied prioritization of the alternatives by the Operations Supervisor. The aggregate scoring combining the preferences of the indicators and the criteria influenced the priorities of the expert. The study could help identify the specific stakeholder values, which might change the acceptability with the end technology selected.

For this study the end scores of the Operations Supervisor indicated a preference for BAF and MBR. MBR stood out as it produced the highest quality *Effluent*. On the other hand BAF was the most prominent alternative as it produced the highest quality *Sludge* as well as it had the highest score for *Aesthetics.* The Operations Supervisor explained that his responsibilities were to follow permits and make sure that society was safe. *Perceived Safety* did not have an influence on the preference of the technologies even though the Operations Supervisor ranked it as the indicator he considered the second most important over all. The reason for the low influence of the indicator *Safety* was due to the scores of the Academic Consultant, which suggested that all four technologies performed to a similar level for the indicator *Safety*.

4.4 Limitations of the Study

This study had two main limitations. First, the ranking of the alternatives required very specific expertise. Second, the consistency issue of AHP led to some confusion. These two points may have influence the accuracy of the prioritization of the alternatives.

One of the weaknesses in the methodology of this study is that only one of the five experts was asked to rank the alternatives on how they perform for each of the 13 indicators. The scores for the alternatives from the Academic Consultant were used to study the separate prioritization of the alternatives for each of the experts according to their own indicator and criteria ranking. The method led to a bias towards the opinions of the Academic Consultant. For the interests of this study, it would have been more practical to use the ranking of the alternatives from each of the experts. The other experts were not comfortable with the task of evaluating the alternatives. Though, the results were skewed towards the interests of the Academic Consultant, the scores still allowed for insights into the impact of different weights on the prioritization of alternatives. The Academic Consultants strong preference for the SBR technology for the indicators *Initial Costs* and *Long Term Costs*, as well as for slight preference for the indicators *GHG* and *Simplicity* lead to it being the preferred alternative overall and by most of the expert. However, the stability in scores, gave an importance to the identification of the Operations

Supervisor and their specific scoring, which was able to influence prioritization of the SBR, MBR and BAF.

Requesting for clarification and revision of scores required different additional explanations for each of the participants. Another limitation of using AHP was the understanding of the ranking process itself. Each of the experts had a different grasp and comfort with the ranking process. One of the experts had previously used pair-wise comparison and understood their significance, while for the other experts it took a longer time to understand the set up of the exercise.

4.5 Recommendations for Future Research

Evaluating the objectives hierarchy and modifying its elements could lead to a clearer, more representative priority ranking of alternatives for future wastewater treatment selection studies (Khan and Faisal, 2008). The findings of the study were used to suggest specific changes for the objectives hierarchy. Additionally, this study ends by considering the potential role of the public future decision-making situations.

4.5.1 Different Indicators

Some of the experts in the study had recommendations for the objectives hierarchy, which they thought would increase its ability to accurately represent their preferences in wastewater treatment. The indicators selected to develop the objectives hierarchy were *Education*, *Policy* and *Technical Safety* (*Figure 32)*. *Education* was an indicator recommended by two of the experts and is also seen in Balkema et al. (2002) and Sahely et al. (2005). The Municipal Manager and Academic Consultant expressed that people must be able to interact and learn from the wastewater treatment systems so that they can become aware of the processes involved and their contribution to wastewater.

In the new objectives hierarchy *Policy* was included. The meaning expressed by the Academic Consultant was used. They suggested that the selection of a more sustainable wastewater system could actually encourage/lead to sustainable changes in policy. This indicator could allow for future WWTPs to be ranked by the way in which they support innovation in sustainable policy developments. Policy issues as well as administrative needs have been considered previously in De Carvalho et al. (2009).

Technical Safety *(Safety – employee)* was also included. The safety of the technology is particularly important as it is directly connected to the safety of employees. The Operations Supervisor and the Municipal Manager made clear the importance of considering workers present at the facilities. The inclusion of those, whose security could be jeopardized, can support the application of decision-making, through conflict avoidance as suggested by Mabee et al. (2004).

These additions to the hierarchy may lead to an improved understanding for what components of wastewater plants make one preferable to another in future studies *(Figure 32)*. In addition to new indicators, a different decision-making method might be used, which could measure the interaction and interdependence among the indicators. For this the extension of AHP, the Analytic Network Process (Saaty, 1996) could be implemented.

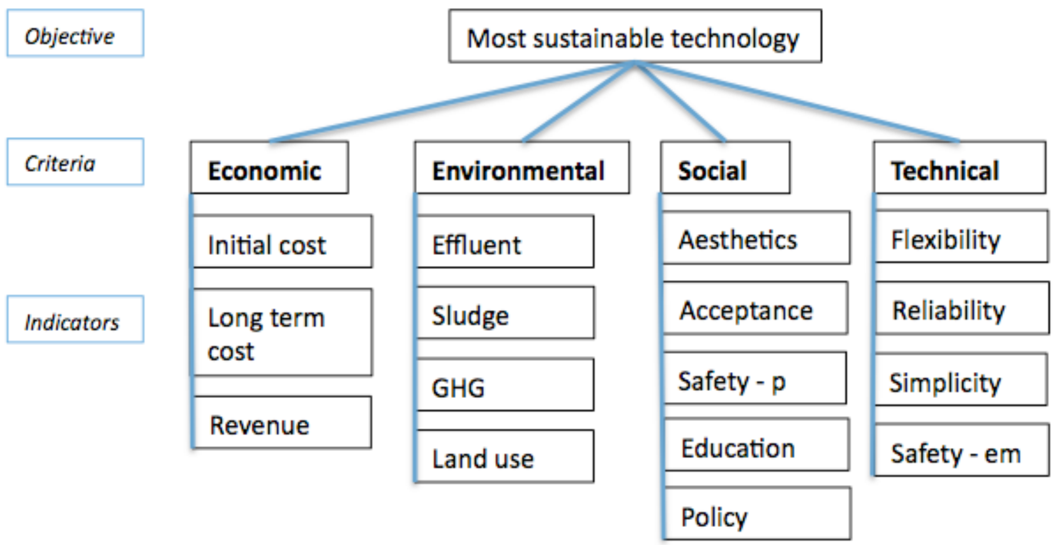


Figure 32 A Revised Objectives Hierarchy - The updated hierarchy includes some new components recommended by the five different experts, which may assist in the selection of the most sustainable technology

This study focused on centralized technologies. In a future study, there could be more opportunities for discussion with the inclusion of a trickling filter and or aerated sludge processes. This would allow an analysis of ways that the four space-saving technologies of the study outperform the conventional technologies. In municipality specific studies, it would be possible to select a set of alternatives more directly suitable to the needs of the local population. Technologies are not static, they can be developed and suited to the specific needs of the municipality (Contreras et al., 2008).

4.5.2 The Inclusion of the Public

This thesis shows that there is no common definition for what the public wants, and how to differentiate among different members of the public. As WWTPs are public infrastructure with public goals, the inclusion of the perspectives of the multifaceted public, could lead to a more holistic understanding of the pros and cons of different alternatives. As seen in the interviews, it was clear for the experts that the public needed to be consulted and needed to agree with the decisions being made about the wastewater treatment facilities.

Similarly to this study, most research on wastewater treatment focus on expert interviews. Especially, the use of the AHP model has been associated with the research of expert judgments. Often the public is affected by decisions but has little understanding or influence on what that final decision might be. The challenge of integrating the public is connected to the knowledge distribution required to develop an informed commentary on the topic (Duke and Aull-Hyde, 2002). Ujang and Buckley (2002) explained that environmental protection must develop alongside both technological know-how as well as the "progress of environmental awareness among the general public" (pp3).

Research in sustainability in wastewater treatment has begun to attempt to integrate "different points of view" to bridge the gap between "urban infrastructure stakeholders and citizens" (Cedano and Martinez, 2007 pp 2). Involvement of different people can "cultivate ownership", decrease in "controversy and social opposition" (Bottero et al., 2011 pp 1215), as well as develop a "higher level of responsibility" towards the technology selected (Mallett, 2007 pp 65). This could support the "buy in" government's need for the selection of wastewater treatment alternatives.

4.6 Conclusion

The study integrates theories on indicator selection with decision-modeling literature for the wastewater field. Literature using AHP modeling for WWTPs often spends more time on the modeling itself, and gives little attention to the reasons and selection of the initial indicators (Chin et al., 2002; Dabaghian et al., 2008; Karimi et al., 2011). Studies on indicator selection often do not speak about the weighting and modeling of their indicators or the selection of wastewater treatment plants (Balkema et al., 2002; Lundin and Morrison, 2002; Singhirrunnusorn and Stenstrom, 2009). Using the perspectives of five wastewater experts on the components of a constructed objectives hierarchy increased insights into potential differences among experts. A better understanding of contentious and influential indicators could support future developments and WWTP upgrade projects by bringing awareness to conflicting goals of different experts (Wiedemann and Femers, 1993; Sahely et al., 2005; Contreras et al., 2008). Additionally, this study showed how different indicator scores could influence the prioritization of alternatives.

4.7 Closing Remarks

The results of this study can be reconsidered by examining some alternate approaches towards sustainability. A distinction can be drawn between sustainability studies that follow top-down approaches, and those that follow bottom-up approaches (Rydin, 1999; Robinson, 2004; Starkl and Brunner, 2004; Fraser et al., 2006; Reed et al., 2006). In addition, small differences in orientation (e.g. eco-centricity vs techno-centricity) can also influence the outcome of a study (Suzuki, 2009; Robinson, 2004).

The complex value systems surrounding the debate of the term ‘sustainability’ have been the subject of much consideration. Nevertheless, there is no consensus on the best practices of combining approaches and perspectives (Rydin, 1999; Robinson, 2004; Reed et al., 2006). Even in light of conflicting interpretations, the concept of sustainability has been considered a useful guide in holistic analyses as well as for the engagement of different stakeholders i.e. the environment and future generations (Haimes, 1992).

To some extent, this study on the use of sustainability indicators in the selection of wastewater treatment technologies followed a techno-centric perspective. Analogously to other research on wastewater treatment selection, this study used expert scores and insights in ways that might be understood as generally consistent with a top-down approach (Ellis and Tang, 1991; Dabaghian et al., 2008; Muga and Michelcic, 2008; Bottero et al., 2012).

The expert opinions were studied through the use of the AHP process, which has been regarded as suitable for the exploration of sustainability goals (Karimi et al., 2011; Bottero et al., 2012). That being said, the decision-analysis technique is focused on expert opinions. As well, AHP is unable to negotiate a more complex array of responses that might include ‘I don’t know’ and thus, it is not suitable for a more bottom-up approach. In this way, the insights are meaningful for sustainability debates, but should not be taken as conclusive. They do not represent the only way to think about wastewater issues. At worst, AHP might be seen as further contributing to the marginalization of popular or alternative voices, in favor of those of the ‘experts’.

To some degree, this expert and top-down orientation is apparent in the results. Overall, participants in the study had a general sense of trust in the abilities of existing technologies and systems dealing with wastewater. There were few concerns expressed with the current political or economic structures. This could imply the adoption of a techno-centric understanding of sustainability by the participants. For instance, the experts were specifically asked to focus on the organization of sustainability provided by the objectives hierarchy of the study. Nonetheless, many comments alluded to the importance of financial needs and limitations. In fact, these economic considerations were fore-grounded even for the non-*economic* criteria. In this way, there were elements of the study design, and outcomes, that potentially resituated the centrality of economic considerations, rather than forcing considerations beyond *Economic* criteria in ways that might be called for from a broader sustainability perspective. Omitting the financial and technological components of an objectives hierarchy may have forced the experts to speak with more depth on the *Environmental* and *Social* indicators. A specific example comes from the Operations Supervisor, who allocated the highest scores to the *Environmental* and *Social* criteria and consequently prioritized the alternative technological options differently from the other four experts. Simultaneously, he primarily expressed a concern with the financial losses that would result from not following *Environmental* permits. This suggests the potential for a different allocation of weights among the indicators had the Operations Supervisor sidestepped the issue of monetary costs. More specifically, his primary concern was *Effluent Quality* due to the regulatory focus on the indicator, and the strict penalties of non-compliance. Additionally, sales of high quality sludge were not considered a contributor to the day-to-day running of a WWTP, and there were few repercussions to for the production of low quality sludge. Had the financial components of these two indicators not been a focal point, their relative importance may have been different compared to each other, and in comparison to the other two *Environmental* indicators.

Another finding was that the experts conveyed sustainability as important and present in "everything" they do. It was interesting to see, however, that overall *Revenue, GHG* and *Feasibility* were amongst the lowest scoring indicators. Arguably, these three indicators are among those most concerned with long term planning, a basis of the sustainability concept. GHGs in particular are often considered the benchmark for sustainability studies (Nardo, 2001). Focusing on wastewater treatment plants, the IPCC (2007) predicted a 50% increase in methane production from worldwide wastewater and wastewater management between 1990 and 2020. One of Metro Vancouver's strategic priorities is to be a "zero net carbon region" (MV-SF, 2010 pp 23). Though each of the experts recognized the significance of GHG output, ultimately, this was not reflected in their scoring due to the fact that they felt there were no specific, strict regulations for WWTPs to adhere to in the fulfillment of the strategic goals.

Numerous wastewater experts have proposed that the ideal sustainable way to approach biological human waste is to develop water-less systems (WHO, 1996; Fittschen and Niemczynowicz, 1997; Otterpohl, 2002). Unfortunately, this has been proven to be a complex goal even in experimental eco-village settings (Fittschen and Niemczynowicz, 1997; Irrgang, 2005). The reality is that the current toilet, sewerage and wastewater treatment infrastructure in place is worth many billions of dollars and provides the basis of waste disposal in municipalities throughout Canada. Therefore there are aspects of the systems that are in place, and path dependencies associated with them, that hold importance in terms of what types of possibilities are imaginable, even when the target is 'sustainability', broadly defined. As such, elements of this research are necessarily limited in that it was largely situated in a techno-centric perspective- the idea that the framework itself is not under scrutiny but rather the focus is on new technologies and systems in order to improve efficiency and accountability (Holt and Viney, 2001). Though this perspective does not represent the environmentalist's ideas (Robinson, 2004), it nevertheless helped to achieve some aims of this research project. Specifically, the results helped to illuminate some key points of tension and coming together of different expert opinions related to various wastewater technologies. Indeed, they exposed the importance of being more open and explicit about the role that varied opinions might play in decision-making around complex issues such as wastewater treatment. Though it is important to keep the ideals of eco-centrism in mind, arguably a techno-centric approach might also be a strong reflection of reality of the current situation i.e. one where possibilities replacing an existing infrastructure may be restricted by budgetary considerations.

Considering the continuum on which eco-centricism and techno-centricism are said to belong (O'Riordan, 1985; Holt and Viney, 2001), we must make small well thought-out steps away from the techno-centric perspective before we can make larger moves. Additionally, a techno-centric approach might be more likely to offer attainable solutions within the CCME (2009) timelines. Ultimately, sustainability is a multi-generational activity (Vanier, 2006). No matter what actions are taken now, we must wait for many decades to understand if the decisions will fulfill their environmentally and socially conscious goals (Lundin and Morrison, 2002).

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Appendices

Appendix A

Letter of initial contact

Request for participation in a study on how differing preferences between wastewater experts impact the identification of 'the most sustainable solution' in space constrained situations

Investigator: M.A. student Hana Sherin Galal,

Institute for Resource Environment and Sustainability, University of British Columbia

Supervisor/Principal investigator: Professor Gunilla Öberg,

Dear --,

I am conducting a study that aims to illuminate how different weights assigned to performance measures by different wastewater experts influence what is considered to be the 'most sustainable solution' between wastewater treatment technologies. My study aims to understand the specific situation of space-constraint and how municipalities in Canada might experience it.

My study focuses on challenges facing a municipality when upgrading their wastewater treatment systems and the tradeoffs that must be taken into consideration.

One part of the study involves carrying out interviews with wastewater experts and I would be most grateful if you were willing to participate, based on your knowledge in the field. Your participation would include filling out a survey to rank wastewater technology indicators while sharing your thoughts. After each set of indicators as well as after the completion of the survey you will be asked questions for further clarification. As you rank the indicators, I will perform some brief calculations, after which you may be requested to renew your scoring. The information will be used as part of my master's thesis work with the Institute for Resources Environment and Sustainability at the University of British Columbia. The study is conducted under the supervision of Professor Gunilla Öberg, who is the principle investigator of a larger project focusing on sustainable wastewater management.

In the survey, you will be asked to rank a collection of performance indicators, which I have compiled as a tool to facilitate the selection of 'the most sustainable wastewater technology' from a selection of four space saving technologies. I will ask you to rank the indicators through two-by-two comparisons eg A is more important than B and C is equally important to B. The method used is based on the process developed for a popular decision support tool called the Analytic Hierarchy Process (AHP).

The entire interview is expected to take approximately one hour, with the possibility of a follow-up interview at a location of your choice. The initial meeting will be organized in the following manner:

1. 10 minutes to review the guidelines together
2. 5 minutes for you to ask me extra questions about the study
3. 40 minutes to fill out the survey and discuss your answers
4. 5 minutes for a closing discussion

With your permission, all interviews will be recorded for later reference.

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If you are willing to participate, I will ask you to sign a letter of consent before our meeting. I will send you a consent form, for you to review ahead of the meeting. The consent form states that you accept filling out the survey and being interviewed. I truly hope that you are willing to participate. Please let me know if you have any questions regarding the research or interview process.

Contact for concern about the rights of research subjects: If you have any concerns about your treatment or rights as a research subject, you may contact the Research Subject Information Line in the UBC Office of Research Services at - or if long distance e-mail to -.

We are hoping to schedule your interviews during June and July. I would greatly appreciate it if you can get back to us and let us know about your availability during these months. I look forward to further contact with you.

Sincerely,

Hana Galal,

M.A. Student Resource Management and Environmental Studies

Institute for Resources Environment and Sustainability (IRES)

University of British Columbia (UBC)

Vancouver, BC, Canada

under the supervision of

Dr. Gunilla Öberg, (Principal Investigator)

Professor,

Institute for Resources Environment and Sustainability (IRES)

University of British Columbia (UBC)

Vancouver, BC, Canada

Appendix B

Interview consent form

Consent to participate in a study on how differing preferences between wastewater experts impact the identification of 'the most sustainable solution'

Investigator: M.A. student Hana Sherin Galal,

Institute for Resource Environment and Sustainability

University of British Columbia

Supervisor/Principal investigator: Professor Gunilla Öberg

Dear -----,

I am conducting a study that aims to illuminate how different weights assigned to performance measures by wastewater experts influence what is considered to be the 'most sustainable solution' in the wastewater realm. My study aims to understand the specific situation of space-constraint and how a municipality in Canada might experience it. As a wastewater expert, I am requesting your participation in the study. Specifically, I will ask you to rank different wastewater technology indicators through a survey instrument. If you agree to participate, your participation will include filling out a survey to rank wastewater technology indicators while sharing your thoughts. After each set of indicators as well as following the completion of the survey you will be asked questions for further clarification. I will use the information for the completion of my Masters thesis at the Institute of Resource Environment and Sustainability at the University of British Columbia.

To provide a bit more specific information on the survey, I have compiled a set of performance indicators that I will ask you to rank in two-by-two comparisons. For example, you might select A as more important than B and C as equally important to B. The method used is based on the process developed for a decision support tool called the Analytic Hierarchy Process (AHP). I would be happy to provide you with more information on the process following the interview, if you are interested.

The entire interview is expected to take approximately one hour, with the possibility of a follow-up interview at a location of your choice. The initial meeting will be organized in the following manner:

5. 10 minutes to review the guidelines together
6. 5 minutes for you to ask me extra questions about the study
7. 40 minutes to fill out the survey and discuss your answers
8. 5 minutes for a closing discussion

With your permission, all interviews will be voice-recorded for later reference.

Your identity and contributions to this study will be kept strictly confidential. The interview will be recorded and transcribed but we will maintain strict access requirements to the materials and no name or title will be used that might identify you or your responses.

Consistent with our confidentiality policy, in the write up of the material for publication, you will be not be referred to by name at any time, instead you will be referred to as a Provincial consultant. Your survey responses will be stored in the AHP software Expert Choice. The transcriptions and results of this study will not be stored online and will be used in a Masters Thesis and may be used in related projects by the wastewater research group at the Institute for Resources, Environment and Sustainability under the supervision of Professor Gunilla Öberg. An electronic copy of the final thesis will be sent to you upon request.

We sincerely hope you will agree to participate in this study. If you have any concerns about your rights as a research subject and/or your experiences while participating in this study, you may contact the Research Subject Information Line in the UBC Office of Research Services at - or if long distance e-mail - or call toll free -.

Taking part in this study is voluntary and you may choose to pull out of the study at any time without giving a reason and without any consequences.

Your signature below indicates that:

- You have received a copy of this consent form for your own records.
- You are clear on what you are being asked to do.
- You consent to participate in this study.

____

Participant Signature   Date

____

Printed Name of the Participant

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Appendix C

Survey cover letter, guide and survey

Cover letter for study on how differing preferences between wastewater experts impact the identification of 'the most sustainable solution'

Investigator: M.A. student Hana Sherin Galal,

Institute for Resource Environment and Sustainability, University of British Columbia

Supervisor/Principal investigator: Professor Gunilla Öberg,

Thank you for agreeing to participate in this study,

I am conducting a study that aims to illuminate how different weights assigned to performance measures by wastewater experts influence what is considered to be the 'most sustainable solution' in the wastewater realm My study aims to understand the specific situation of space-constraint and how municipalities in Canada might experience it.

Analytic Hierarchy Process (AHP), a decision support tool commonly used by governments and businesses, has been selected to facilitate and illuminate the decision making process.

An 'objectives hierarchy' has been created where the wastewater treatment plant (WWTP) decision process has been broken down into some of its measurable criteria and indicators. For this study, the term 'objective' is being used for the overall goal, which is to select the 'most sustainable technology.' The second level of the hierarchy is referred to as the 'criteria', and the third level is made up of 'indicators'. Below (Figure 2) is an illustration of which indicators contribute to each of the criterion. The next page will give more detail on what the indicators represent and how they should be measured.

You are being asked to begin the survey after first reading the following four pages of this package. Please do not hesitate to ask questions if anything in the document is unclear.

In the survey you will be asked to rank the components of the objectives hierarchy with regards to how important you believe them to be towards the fulfillment of the overall objective - sustainability. You will be asked to use the 1 - 9 ranking scale for a series of 'pair-wise' or two-by-two comparisons, consistent with the AHP framework (examples follow). You may be requested to re-rank the indicators. As part of the study, I also ask that you share your thoughts and rationale with me while you fill out the survey. After each set of indicators, as well as after the completion of the survey I will be asking you questions for further clarification.

This meeting will be organized in the following manner:

9. 10 minutes to review the guidelines together
10. 5 minutes for you to ask me extra questions about the study
11. 40 minutes to fill out the survey and discuss your answers
12. 5 minutes for a closing discussion

To begin, below I provide a few examples to demonstrate how you might rate the different criteria and indicators. Following the ranking example, I will provide a few more details on the 'objective hierarchy' I developed. The indicators selected for this study based on a review of the literature on wastewater technologies and available solutions.

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Ranking Sample

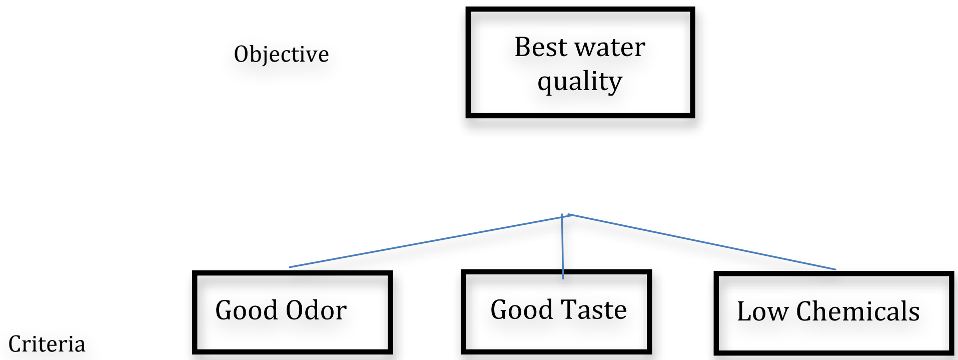

Figure 1 - A sample objectives hierarchy

Below is a sample of how someone, **according to their own opinions**, might rank the *Criteria* and their importance in fulfilling the *Objective*; in this case, the best water quality.

Score 1: Good water odor ***9*** 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 Good water taste

Score 2: Good water odor 9 8 7 6 5 4 3 2 ***1*** 2 3 4 5 6 7 8 9 Low chemicals

Example Score 1: Rank of 9 indicates that for this respondent having a *good water odor* is 'extremely more important' than having a *good water taste* to fulfill the *Objective (best water quality)*.

Example Score 2: Having *a good water odor* is 'equally important' as having *low chemicals* to fulfill the *Objective (best water quality)*.

Meaning of ranking scale

Below are the ranking numbers to be used in this survey. These are the standard verbal expressions of the numbers used in 'Analytic Hierarchy Process' ranking (Saaty, 2002). *The AHP framework uses a verbal interpretation of the scale, which might appear slightly unnatural. I ask you to oversee this for our purposes today, and instead, focus on the relative importance you assign to each of the goals towards the overall objective of 'the most sustainable wastewater solution'.*

1 Equally important

3 Moderately more important

5 Strongly more important

7 Very strongly more important

9 Extremely more important

2, 4, 6, 8 Intermediate judgment values

	1	**9**	**2,4,6,8**
Clarification	Components have the same importance in fulfilling the objective	One component is 9 times more important than the other in fulfilling the objective	To be used when your value falls between the main markers

The Objectives Hierarchy for Wastewater Treatment Alternatives

The 'objectives hierarchy' used for this research project was derived drawing from the:

- *Wastewater treatment literature*
- *Canadian wastewater treatment guidelines*
- *Interviews with experts in Metro Vancouver*

The criteria and indicators being used in this interview/survey have been preselected as part of our research process and design. Of course, different people will have different ideas with respect to the most appropriate or relevant components of the hierarchy. For this interview/survey, however, you are only asked to contribute your scoring for the pre-selected criteria and indicators. This should be done from your perspective from your position or duties in your profession. The objectives hierarchy below has been specifically derived with an overarching focus on 'sustainability', and as such includes social, environmental, economic and technical components.

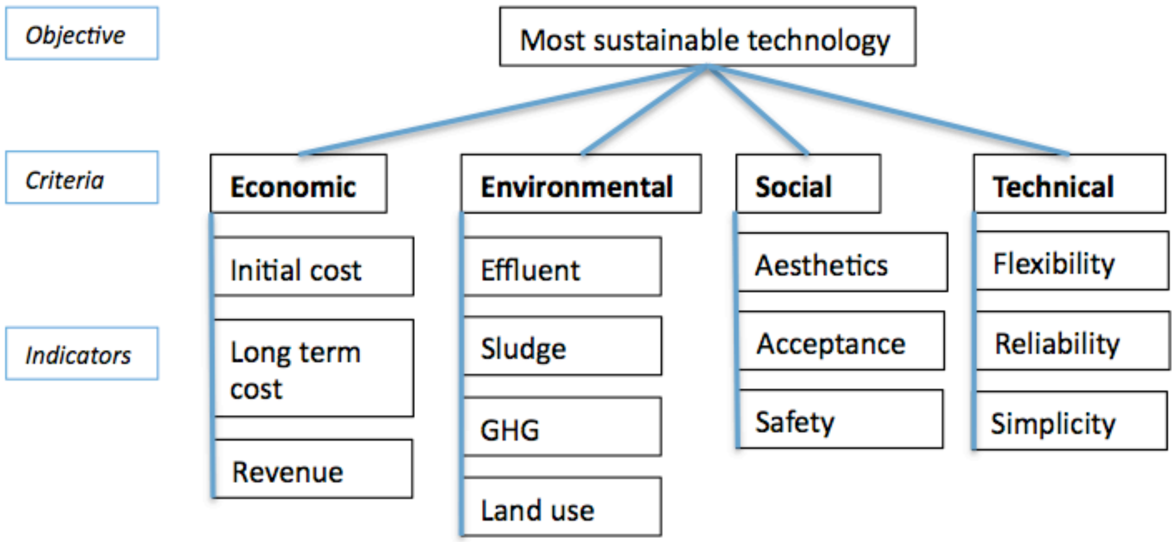

Figure 2 – The objectives hierarchy for the Metro Vancouver case study

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Indicator measures

Below are the measures for each of the indicators. Please familiarize yourself with these units before ranking the indicators and criteria in the survey.

Economic

Initial cost - Capital cost of initial construction and establishment of WWTP
Long-term cost - Cost of maintenance and operations over 50 years
Revenue - Revenue made over 50 years through the sale of recoverable resources such as energy

Environmental

Effluent quality **-** mg/l of BOD5 and TSS in final water output from WWTP
Sludge quality **-** Pathogens and heavy metal content
Green House Gas - Carbon Dioxide and Methane output in metric tons/day
Land use - Amount of hectares of land the technology requires

Social

Aesthetics - Amount of complaints about smell, construction and visuals by society
Safety - Society's perceived safety
Cultural acceptance - Amount of cultural and religious comfort felt by society

Technical

Flexibility - Ability to perform at desired level in light of potential future climate change, expansion requirements or unexpected loading
Reliability - Risk of failure
Simplicity - Ease of construction, use and repair

We are now ready to go on to the pair-wise comparisons

Please do not hesitate to ask questions if anything up to this point is unclear.

In the following page you will find the computer based ranking survey. You will be given time to rank each group of pair-wise comparisons according your preferences and you are asked to share your thoughts while you are carrying out the ranking. After each set of comparisons you will be given your overall ranking of the indicators as well as you inconsistency score. If you score is larger than 0.10, you will be asked to redo your scoring. I will also ask you some questions between the sets of pair-wise comparisons and after you have finished filling out the survey.

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Value Elicitation Survey

Please compare the importance of the INDICATORS against each other in regards to having the most ECONOMICALLY sustainable wastewater treatment technology:

Initial capital cost	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Long term cost
Initial capital cost	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Revenue
Long term cost	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Revenue

Please compare the importance of the INDICATORS against each other in regards to having the most ENVIRONMENTALLY sustainable wastewater treatment technology:

Green House Gases	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Effluent quality
Green House Gases	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Sludge quality
Green House Gases	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Land use
Effluent quality	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Sludge quality
Effluent quality	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Land use
Land use	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Sludge quality

Please compare the importance of the INDICATORS against each other in regards to having the most SOCIALLY sustainable wastewater treatment technology:

Aesthetics	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Safety
Aesthetics	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Cultural acceptance
Safety	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Cultural acceptance

Please compare the importance of the INDICATORS against each other in regards to the selection of the most TECHNICALLY sustainable wastewater treatment technology:

Flexibility	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Reliability
Flexibility	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Simplicity
Reliability	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Simplicity

Please compare the importance of the CRITERIA against each other in regards to the selection of the most sustainable wastewater treatment technology:

Economics	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Social
Economics	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Technical
Economics	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Environment
Social	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Technical
Social	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Environment
Environment	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Technical

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Interview script (to be read by interviewer)

Thank you once again for making time for me to come in and interview you. Before we get started with the interview and survey, I wanted to give you the consent form, which I sent you over email. After you sign that, let me know if you have any questions or concerns in terms of the purpose of this study and your part in it.

I have the recorder here, which I will be using with your permission to record our conversation throughout the ranking and interview. This recording will be transcribed and stored.

(Hand out consent form and collect it back)

Thank you, now let us get started with the interview and survey.

Questions for between indicator sets:

What you think that others in your field or similar position would value these indicators?

Help me understand the reason that ----- is so much more important than-----

What made you select those numbers?

What has happened in your previous experience when certain indicators have been ignored?

Do you think that there is an indicator where others will have very different scores?

Questions for the end of the survey:

To get started how did you feel about the objectives hierarchy, did you feel that it covered the points that you believe to be important?

What do you think about the 4 main criteria? Can you tell me about their ranking, and why they were so similar/so different?

Overall what indicator is the most important to you?

Which indicators did you think were missing?

Which indicators did you not think were not necessary?

What do you think about the goal of having a ‘sustainable system’?

In your day-to-day decision making how do you view sustainability?

Where do you feel the biggest struggle between short term and long term?

What are the most important technological frontiers?

What are the most important challenges?

What are your reflections on the state of wastewater treatment in general?

From the top of your head, which technology would you say is the most sustainable? – Vertical Deep Shaft Bio-Reactor, Sequencing Batch Reactor, Membrane Biological Reactor, Biological Aeration Filters

At the end of study:

Thank you very much for your time, I appreciate you speaking with me and sharing your knowledge and perspective on the topic.

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Appendix D

Ranking of Alternatives

Institute for Resources, Environment & Sustainability

4th Floor, 2202 Main Mall

Vancouver, BC Canada V6T 1Z3

Website: www.ires.ubc.ca

Cover letter for study on how differing preferences between wastewater experts impact the identification of 'the most sustainable solution'

Investigator: M.A. student Hana Sherin Galal, Institute for Resource Environment and Sustainability, University of British Columbia

Supervisor/Principal investigator: Professor Gunilla Öberg,

Thank you for agreeing to participate in this study,

I am conducting a study that aims to illuminate how different weights assigned to performance measures by wastewater experts influence what is considered to be the 'most sustainable solution' in the wastewater realm. My study aims to understand the specific situation of space-constraint and how municipalities in Canada might experience it.

Analytic Hierarchy Process (AHP), a decision support tool commonly used by governments and businesses, has been selected to facilitate and illuminate the decision making process.

An ‘objectives hierarchy’ has been created where the wastewater treatment plant (WWTP) decision process has been broken down into some of its measurable criteria and indicators. For this study, the term ‘objective’ is being used for the overall goal, which is to select the ‘most sustainable technology.’ The second level of the hierarchy is referred to as the ‘criteria’, and the third level is made up of ‘indicators’. The fourth level is made up of the ‘alternatives’, which are different wastewater treatment technologies. Below (see Figure 2) is an illustration of which indicators contribute to each of the criterion. The next page will give more detail on what the indicators represent and how they should be considered.

You are being asked to begin the survey after first reading the following four pages of this package. Please do not hesitate to ask questions if any part of this document is unclear.

In the survey you will be asked to rank four different wastewater treatment technologies and how you prefer their performance on the 13 different indicators. You will be asked to use the 1 - 9 ranking scale for a series of ‘pair-wise’ or two-by-two comparisons, consistent with the AHP framework (examples follow). Due to the set up of the AHP model you do not need to have exact knowledge to fill out any of the scores. You will be expected to react on your subjective knowledge.

Below I provide a few examples to demonstrate how the ranking process works with different criteria and indicators. Following this example, I will provide a few more details on the ‘objective hierarchy’ I developed. The indicators selected for this study based on a review of the literature on wastewater technologies and available solutions.

Ranking Sample

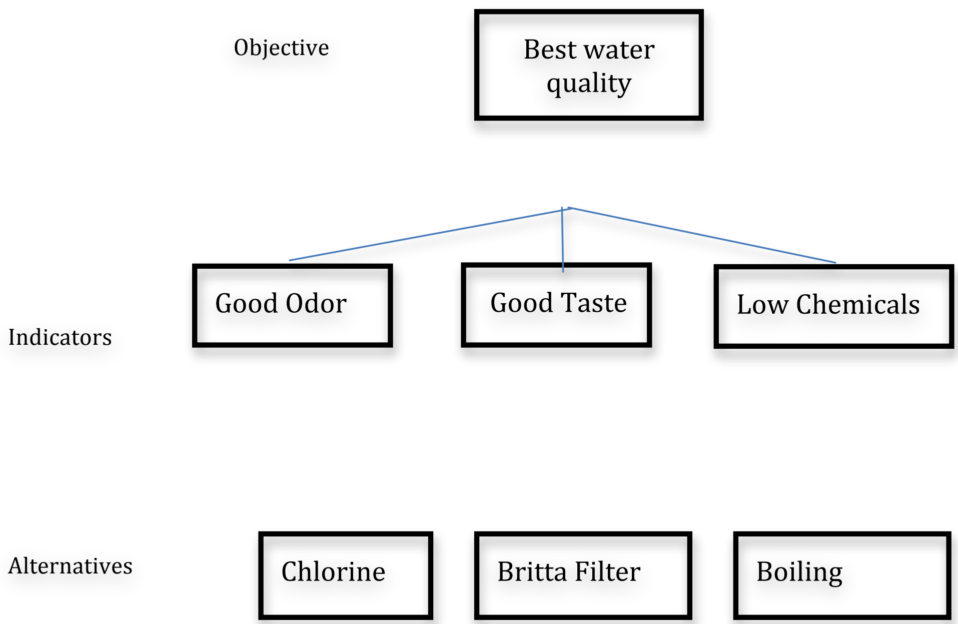

Figure 1 - A sample objectives hierarchy

Below is a sample of how someone, **according to their own opinions**, might prefer the alternatives performances for *'Good Odor'*

Score 1: Chlorine 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 **9** Britta Filter

Score 2: Boiling 9 8 7 6 5 4 **3** 2 1 2 3 4 5 6 7 8 9 Chlorine

Example Score 1: Rank of 9 indicates that this respondent prefers the performance of the ***Britta Filter*** '*extremely more'* than ***Chlorine*** in terms of the water odor it produces.

Example Score 2: The respondent prefers the water odor after ***Boiling,*** *'moderately more'* than the water odor after ***Chlorination***

Meaning of ranking scale

Below are the ranking numbers to be used in this survey. These are the standard verbal expressions of the numbers used in 'Analytic Hierarchy Process' ranking (Saaty, 2002). *The AHP framework uses a verbal interpretation of the scale, which might appear slightly unnatural. I ask you to oversee this for our purposes today, and instead, focus on the relative preferences you assign to the performance of the alternatives.*

2 Equally preferred

4 Moderately more preferred

5 Strongly more preferred

7 Very strongly more preferred

9 Extremely more preferred

2, 4, 6, 8 Intermediate judgment values

	1	**9**	**2,4,6,8**
Clarification	The alternatives have the same performance	The performance of an alternative is preferred 9 times more than the other alternative	To be used when your value falls between the main markers

The Objectives Hierarchy with Alternatives

The 'objectives hierarchy' used for this research project was derived drawing from the:

- *Wastewater treatment literature*
- *Canadian wastewater treatment guidelines*
- *Interviews with experts in Metro Vancouver*

The criteria and indicators being used in this survey have been preselected as part of our research process and design. Of course, different people will have different ideas with respect to the most appropriate or relevant components of the hierarchy. For this interview/survey, however, you are only asked to contribute your scoring for the pre-selected criteria and indicators and the four selected alternatives. This should be done from your perspective from your position in your profession. The objectives hierarchy below has been specifically derived with an overarching focus on 'sustainability', and as such includes social, environmental, economic and technical components.

Indicator measures

Below are the measures for each of the indicators. Please familiarize yourself with these units before ranking the indicators and criteria in the survey.

Economic

Initial cost - Capital cost of initial construction and establishment of WWTP
Long-term cost - Cost of maintenance and operations over 50 years
Revenue - Revenue made over 50 years through the sale of recoverable resources such as energy

Environmental

Effluent quality - mg/l of BOD5 and TSS in final water output from WWTP
Sludge quality - Pathogens and heavy metal content
Green House Gas - Carbon Dioxide and Methane output in metric tons/day
Land use - Amount of hectares of land the technology requires

Social

Aesthetics - Amount of complaints about smell, construction and visuals by society
Safety - Society's perceived safety
Cultural acceptance - Amount of cultural and religious comfort felt by society

Technical

Flexibility - Ability to perform at desired level in light of potential future climate change, expansion requirements or unexpected loading
Reliability - Risk of failure
Simplicity - Ease of construction, use and repair

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The Wastewater Treatment Technologies

Wastewater treatment systems can vary depending on requirements from specific locations. Due to the CCME (2009) regulations please consider the following technologies and their performances when they are set up to produce effluent at the ***most*** *25 mg/l BOD5 and 25 mg/l TSS.*

Below are the four wastewater treatment technologies you are being asked to rank:

Biological Aerated Filter (BAF)

- Made up of tanks filled with media that filter influent wastewater
- Has three main stages; solid (biomass on the filter media), liquid (the wastewater influent) and gas (the oxygen bubbled through the liquid)

Vertical Deep Shaft Bio-Reactor (VSBR)

- A high-rate aerobic activated sludge process
- Made up of two vertical shafts between 0.76 – 6 meters in diameter and up to 150 meters deep

Sequencing Batch Reactor (SBR)

- Six main stages are: filling, settling, clarifying, removal of effluent, wasting sludge and remaining idle
- Produces low quantities of high quality sludge

Membrane Bio-Reactor (MBR)

- Modernly developed aerobic system
- Contains an internal water permeable membrane

Appendix E

Description of AHP model function

The AHP objectives hierarchy space constrained municipalities was developed into four levels. The first level has the overall objective, which is 'to select the best wastewater treatment technology'. The second level has four criteria (i.e., the quadruple bottom line of sustainability: made of the social (s), economic (c), environment (e) and technical components (t)), and their priorities are derived from a reciprocal matrix of pair-wise comparison with reference to the overall objective of the first level. The third level is made up of thirteen indicators, four under 'Environmental', three under the 'Economic', 'Social' and 'Technical' criteria. Each of the indicator weights belonging to each of the criteria is derived from a reciprocal matrix of pair-wise comparisons with reference to their super-ordinate criteria. Finally, the fourth level has four alternatives (the secondary wastewater treatment technologies: MBR, SBR, BAF and VSBR, which are to be prioritizes in accordance to their fulfillment of the indicators. The procedures are as follows:

Step 1 Define Matrix Ai as the indicator matrix with super-ordinate criteria i (where fc;e,s,tg)of dimension mi_mi (where mc , me and ms =3 and mt = 2); with pair-wise comparison of the indictors with respect to their comparative importance in their fulfillment of the super-ordinate criteria as the elements of Ai: Then find the priority vector of each matrix Ai and denote it by Xi:: It is important to recall that each of these matrices are reciprocal matrices. For example the economic indicator matrix is given by,

Step 2 Define Matrix G of dimension 4 by 4 as the criteria matrix, with pair-wise comparisons of the parameters with respect to the overall objective as the components of G. Then find the priority vector of matrix G and call it XG:

Step 3 Take the 4 wastewater technology alternatives to be ranked, and form a total of 13 reciprocal matrices Mij(where i represents the criteria and j an indicator belonging to that criteria:s1 - s4; e1-e4; c1; - c4; t1 and t2) of size 4 _ 4, each of which consists of elements of pair-wise comparisons of the 4 technologies with respect to each single indicator. Find the priority vector (of dimension 4) for each of these vectors and call it Xij:

Step 4 For each criteria i; take all of the indicators belonging to that criteria. Then for a composite matrix Li by taking Xij as columns in Li in sequence so that:

Subsequently, we obtain for each criteria i; a resultant priority vector, Yi; of dimension 4, by multiplying matrix Li with the priority vector Xi; or Yi

We will, thus, end up with four priority vectors: Yc; Ye; Ys; Yt:

Step 5 Take the four resulting priority vectors from Step 4, and create a matrix, call it L~; by taking each Yi as columns in sequence so that:

and multiply L~ with XG (see step 2) to form priority vector V; i.e.,

From the result of V, the ranking of the wastewater alternatives can be obtained in their fulfillment of the overall objective.

Appendix F

Description of Alternatives

Biological Aerated Filter

The System

The Biological Aerated Filter (BAF) was first developed in 1913 in the UK but was not utilized for many decades afterwards. BAF began to increase in popularity after its modern update in the 1980s. During this time a version was invented that did not require sedimentation tanks (Rogalla et al., 1990) and thus decreased its footprint.

The BAF system has a very short hydraulic retention time and requires little to no pre or post treatment. Therefore, a wastewater treatment plant using BAF has a relatively high capacity for its low surface area. BAF is made up of tanks that are filled with media that filter the influent wastewater. BAF can be seen to have three main stages; solid (biomass on the filter media), liquid (the wastewater influent) and gas (the oxygen bubbled through the liquid) (Pujal et al., 1992).

The vertical tank can be set underground, and wastewater and oxygen is sprayed in together either from the top or the bottom of the tank. BAF implemented in a system after pretreatment and preliminary mechanical separation, with no post treatment. Oxygenation is used to increase mixing of the liquor and speed up reaction time. The filter media is usually made of irregular, rough surfaced plastic spheres supported by a gravel bed. The filter media is used to allow thick layers of biological microorganisms to develop. The biomass on the media is an essential component of the wastewater cleaning process, however rapid growth can also lead to blockages (*figure x*). To remove the biomass, BAF WWTPs must regularly be 'backwashed'.

The wastewater produced from backwashing must be stored separately and is gradually returned into the wastewater treatment process (Mendoza-Espinosa and Stephenson, 1999). BAF has been used for both secondary and tertiary biological wastewater treatment, and it can be controlled and operated to the specific needs of each municipality implementing it.

Advantages and Disadvantages

BAF has many advantages over the conventional trickling filters and activated sludge processes, however, there are some inconveniences that have kept BAF from becoming a popularly implemented technology (*seen in Table 1).*

Table 1 – The advantages and disadvantages of BAF technology (Condren, 1990; Pujol et al., 1992; Mendoza-Espinosa and Stephenson, 1999)

Advantages	Disadvantages
Remains effective in cleaning wastewater even with unexpected loadings and temperatures	In lower winter temperatures nitrification becomes less reliable
Underground storage reduces footprint and visual pollution	High initial construction costs from rock excavation
Has been proven reliable in densely populated and coastal zones, in Canada and internationally	Has not been used in many different municipalities
No extra sedimentation tanks required	There is a regular filter clogging
Flexible and operable to fit specific needs	Does not produce high quality biosolids due to speed of suspended solids removal
Energy and manpower saving	Backwashing requires extra electricity and storage facilities
Effluent can be reused domestically	High maintenance costs

BAF Implemented in Canada

There are dozens of examples of BAF being used in municipalities throughout Canada. The Ravensview WWTP in Kingston, Ontario opened in 2009, and became one of the largest BAF WWTP in North America. The construction space available for the WWTP upgrades required a technology that was compact. The upgrade cost, at 115 million dollars, was the ‘largest capital project’ in Kingston history (Kingston, 2012). The effluent outfall of the Ravensiew WWTP is 150 m from shore and has been positioned at a 20 meter depth. The effluent is released into the St. Lawrence River is eventually fed into Lake Ontario. The higher effluent quality provided by BAF promote the environmental health of the flora and fauna of river and lake. Through the use of the BAF technology, Kingston had an increase in capacity from 72,800 m3 per day to 95,000 m3 per day (Waterworld, 2009). The biogas being produced by the WWTP process is used to produce energy and the excess methane is flared off (Kingston, 2012).

With the success of the BAF technology in various Canadian municipalities, Victora, British Columbia (Stantec, 2009) and North Shore, Metro Vancouver, British Columbia (Fidelis, 2011) are both currently considering BAF for their WWTP upgrades in order to comply to new CCME (2009) standards as well as their respective population growth.

Vertical Deep Shaft Bio-reactor

The System

Originating in the United Kingdom, the VSBR can be seen as a high-rate aerobic activated sludge process. The main component of the system is made up of two vertical shafts that can be 0.76 to 6 meters in diameter and up to 150 meters deep (Sampa and Tanaka, 1995; Shammas et al., 2009). Due to the vertical implementation of the technology, it uses only 20% of the space of aerated sludge processes.

The oxidation, mixing, and saturation zones distinguish the different segments of the pipe length-wise. Additionally, each of the pipes is made of different layers, which make up its width; a reactor casing, air space, influent space, the down-comer and the extraction line. The down-comer in each of the two main shafts is a concentric pipe that delivers liquid to the bottom of the shaft. The wastewater comes back to the surface of the pipes in the space between the inner pipe and the outer pipe. Compressed air, which is also added into the pipes, increases oxygenation and circulation (between 0.9-1.5 m/s), making the VSBR a high-speed process. The air injection depth and pressure will vary depending on the required effluent quality (Shammas et al., 2009). Solids, which float to the top of the pipes, are removed through a skimming process and pumped to sludge digestion tanks. Though the VSBR process is functional without primary treatment, preliminary treatment is recommended to reduce clogging.

Advantages and Disadvantages

Though VSBR has the lowest footprint of any secondary treatment technology available, its unique set up and costs reduce its popularity (*Table 2*).

Table 2 – The characteristics of deep shaft bioreactors (Sampa and Tanaka, 1995; Shammas et al., 2009)

Advantages	Disadvantages
Has proven successful where implemented	Not commonly used
Is capable of removing volatile organic compounds	Vertical functioning of technology makes regular check ups and repairs difficult
Low operating costs	High implementation and maintenance costs
Low visual and odor impacts	Not applicable to coastal regions or areas with high groundwater levels
Can handle high concentrations of wastewater at high speeds	
High oxygen transfer efficiency means that there is no need for extra mixers	Requires high amount of energy for production of strong consistent air pressure
No extra aeration required for nitrification	
Near full nitrification possible at all temperatures	
High quality biosolids	
Expansion of WWTP does not require much extra space or staffing	

VSBR Implemented in Canada

In 1996, Chevron Canada LTD petroleum refinery in Burnaby, British Columbia, uses a VSBR treatment system (Wholewater, 2012). VSBR was selected due to the very small plot of land available for construction, the very sensitive ecosystem surrounding the inlet, and the Burnaby residents living only 18 meters away (EC, 2010). The VSBR in Burnaby cleans the water used during the oil refining process. The wastewater is made up of oils, grease, hydrogen sulfides and other chemicals. The WWTP was given a British Columbia Water and Waste Association Industrial Pollution Control award in 1997 (EC, 2010) due to its performance. Even with very concentrated contaminants, the VSBR has proven itself robust against changes in influent flow strength and PH, and has been capable of regularly producing an effluent of less than 5 mg/l BOD and TSS (Wholewater, 2012).

Sequencing Batch Reactor

The System

Another technology developed in the United Kingdom, the Sequencing Batch Reactor (SBR), was invented in 1914. By developing the aeration process, nitrification times were reduced from 5 weeks to 9 hours. When WWTPs increased in popularity for the treatment of domestic/municipal waste, SBR was unused due to its complicated fill-and-draw and valve system. In the 1980s the USEPA revived the SBR system with new upgrades. The Clean Water Act of 1997 further intensified the USEPA's interest in the system as they attempted to support the development of innovative wastewater treatment systems (Arora et al., 1985).

SBR is a six-stage process. The treatment involves introducing the wastewater into the tanks one batch at a time rather than in a consecutive flow. The process includes the filling of the tank, the aeration of the liquid and a one-hour settling time where the sludge drops to the bottom of the tank. After the sludge has been separated, the cleaned effluent is removed from the top of the tank through a decanter and moved to another tank. Between cycles and while the excess sludge is wasted, the SBR tank remains idle. Some of the activated sludge is returned to the SBR tank to increase the productivity of the microorganisms (ABL, 2012).

Advantages and Disadvantages

Sequencing Batch Reactors (SBR) stand out for their production of high quality sludge as well as the low costs associate with operations, however, the highly skilled regular supervision required have hindered their popularity *(see Table 3*).

Table 3 – The Advantages and Disadvantages of implementing an SBR wastewater treatment system (Arora et al., 1985; Carucci, 1999; Zaiat et al., 2001; Lui and Lui, 2006)

Advantages	Disadvantages
Cost saving possible through low operations costs	Requires very precise reliable supervision of each stage of functioning with potential difficulties overnight
High quality and low quantity sludge with the ability to contain and reuse sludge for an unlimited time	Can handle low temperatures only if the biomass concentration increases
Can handle shock loads without leading to difficulties with effluent	Settling time is up to 25% of total cycle time
COD removal and nitrification is consistent without requiring additional chemical treatment	Removal of phosphorus requires addition of the chemical compound aluminum sulphate
Can function in cool and warm climates	Slow start up times after idling
Increases energy conservation and recovery	Lack of general knowledge about feed strategies
High flexibility	Overgrowth of filamentous bacteria from long solids retention and oxygen deficiency can cause process instability

SBR Implemented in Canada

The Sequencing Batch Reactor is an advanced wastewater treatment system that has only increased in its implementation in Canada over the last decade. The City of Cardinal in Ontario developed their Sequencing Batch Reactor WWTP in the late 1990s (Premiertech, 2009). The expansion of the City required that Cardinal build a WWTP that would be able to comply with strict CCME regulations.. SBR was the selected method of treatment due to its ability to function in light of changes in peak and average flows, and its ability to produce reliable clean effluent with a Phosphorous output of below 1 mg/l. Later, the provincial government began to encourage a 'Zero Discharge' from the infrastructure of its municipalities. To avoid legal repercussions wastes were reused and recycled, and thus pollution was significantly reduced. Due to the ease of system arrangement, SBR allowed the City of Cardinal to easily adjust and comply with new standards.

Membrane Bio-Reactor

The System

A Membrane Bio-Reactor (MBR) system was first implemented in 1969, with significant changes in the technology developing over the last 10 years (Ng et al., 2007). With MBR, biological treatment is combined with membrane filtration, leading to a reliable high quality of effluent. The membrane in MBR is only permeable to water and is submerged in an activated sludge process. The water is drawn through the membrane, and the sludge remains on the membrane (van Beenen, 2002). Air released from the bottom of the tank promotes aerobic conditions for the microorganisms growing on the membrane. MBRs are created either with an external or an internal membrane, however the internal membrane is more popular as it uses less energy and reduces the intensity of fouling (Ng et al., 2007).

Advantages and Disadvantages

There are various operational advantages of using the MBR technologies however the system also comes with complexities (Table 4)

Table 4 - A presentation of some of the main advantages and disadvantages of MBR wastewater treatment systems (Engelhardt et al. 1998; Ahn et al., 1999; van Beenen et al., 2007; Ng et al., 2007)

Advantages	Disadvantages
Changes in organic loading do not change high quality of effluent	Is not capable of reducing the discharge of many industrial/household chemicals and pharmaceuticals
Membrane filtration can be controlled off-site without professionals supervising the WWTP	System analysis and performance predictions still uncertain
The simple and automated system makes it accessible to communities with less reliable labor	Filters are easily damaged through fouling
Membranes can be retrofitted with other technologies lowering expansion costs	Most commonly in use in small communities
Total nitrogen removal is possible even in cold weather	Metal salts required for phosphorus reduction
Resilient against mechanical failures	High cost of construction
	Chemicals used in backwashing can be toxic to microorganisms
	Higher nutrient concentration reduces organic contaminant removal
	Difficulties with accommodating peak flows

Implemented in Canada

A Membrane Bio-Reactor (MBR), scheduled to enter service in 2012, is located in Brandon, Manitoba. Responding to the CCME 2009 regulations, as well as the increase in residents and their high demand for water, the municipality invested in the expansion of their young WWTP. The construction will become the largest MBR WWTP in Canada. The enlarged facility will have the ability to treat the wastewater from a growing population and will also be able to treat the concentrated industrial wastewater from its growing manufacturing industries. The stainless steel membrane tanks minimize site footprint. The quality of the effluent is expected to be able to combat future water demand through water reclamation that can be used in industry and by other consumers (Journal of Commerce, 2010).

Appendix G

The Fidelis Report

The Fidelis Consultancy report

The triple-bottom-line analysis developed by Fidelis was established in order to assist in the selection of a new wastewater treatment technology. The Fidelis report created a collection of indicators through the group's study of the Metro Vancouver situation. The Fidelis consultancy group was hired in 2010 to evaluate different opportunities for integrated resource recovery systems and their corresponding technologies and as well as recommend a preferred replacement technology. Metro Vancouver asked for a wide variety of details from the Fidelis report;

- Identify and quantify resource flows
- Identify and quantify potential uses and users of resources
- Identify possible locations and scenarios for resource recovery facilities
- Conceptual design of the waste treatment and resource recovery facilities
- Produce a preliminary business case assessing incremental costs and revenues
- Identify the broader policy and governance implications of Integrated Resource Recovery
- A triple-bottom-line analysis

▪ Fidelis (2011)

In following with Metro Vancouver's sustainability goals, the selection of the scenarios took place under the framework of the triple-bottom-line (social, economic and environmental) of sustainability. The report reviewed six different systems representing three different technologies that were recommended by Fidelis as alternatives, which all fulfill CCME regulations but were each different in design. The Fidelis report was release at the end of March 2011.

The decision-analysis was done through the selection of a baseline technology and ranking the other technologies according to their comparative performance. Scenario 2 was a system selected as directly fulfilling Metro Vancouver's liquid waste management plan. The alternative scenarios were ranked by the Fidelis team members, according to how they believed the technologies fulfilled the triple-bottom-line. The ranking scores allocated were between -5 and +5. This was then displayed in table where the alternatives were given the average of all of the Fidelis team marks. The total amount of minus points as well as the total amount of plus points were added together to give the final scoring of the scenarios and ultimately compared them against each other.

This study showed that Scenario 4 was the most inexpensive, however, Scenario 3 was the most sustainable and so was the most recommended by the consultancy firm (Fidelis, 2011). The chart format of the triple-bottom-line analysis was organized into an objectives hierarchy to allow for another visualization of the ranking process.

Appendix H

Indicator Selection

Economic

Initial Costs

Measure: Capital cost of initial construction and establishment of WWTP

Directionality: Lower costs indicate a higher performance

Even though the focus on monetary value is believed to be the fallacy of past developments (Brunner and Starkl, 2004; Muga and Mihelcic, 2008), the financial components of any project must continue to be prominent in the minds of decision-makers (Vanier, 2006; Dabaghian et al., 2008; Fidelis, 2011). *Initial capital cost* is the most standard short-term indicator for municipal infrastructure. It has been used in both one dimensional financially based cost studies, as well as sustainable MCDM wastewater analyses (Hellstrom et al., 2000; Kholgi, 2001; Guanming, 2007; Anagnostopoulos et al., 2007; Dabaghian et al, 2008; Karimi et al., 2011; Bottero et al., 2011). Initial costs are a crucial component to an infrastructure study. In some cases the cost of compensating the local people to allow the building of a WWTP has been included (Adenso-Diaz et al., 2005; Anagnostopoulos et al., 2007). The distribution of the cost burden was not mentioned, as the potential taxing of users would be directly connected to the cost of the technology. Though it is the most standard method of measurement, Anagnostopoulos et al. (2007) found that the importance of *Initial Costs* was contested between different stakeholders, with a particular discrepancy between the prefecture authorities and the municipal authorities. 'Initial costs', similar to the other two indicators under the criterion *Economic*, are being measured in Canadian Dollars.

Long Term Costs

Measure: Cost of maintenance and operations over 50 years (no decommissioning)

Directionality: Lower costs indicate a higher performance

'Long term costs' was considered an important indicator to be included under 'Economic'. Initial capital costs, operations, and maintenance costs are generally used along side each other (Sahely et al., 2005; Guanming, 2007; Anagnostopoulos et al., 2007; Dabaghian et al, 2008; Karimi et al., 2011). It is useful to separate the two costs because a technology can be inexpensive to set up, but very expensive to maintain, allowing for a discussion of trade-offs and intergenerational justice (Loucks, 1997). The operations and maintenance allows for the inclusion of the longitudinal affordability of the WWTP alternatives (Singhirrunnusorn and Stenstrom, 2009).

Revenue

Measure: Revenue made over 50 years through the sale of energy, reclaimed water and nutrients

Directionality: Higher revenue indicates higher performance

'Revenue' was selected as an indicator in order to include Integrated Resource Recovery (IRR) into the objectives hierarchy. Historically, decisions on the design and selection of infrastructure have primarily been based on finances (Sahely et al., 2005; Balkema et al., 2002). The triple-bottom-line concept still includes finances, as a sustainable technology should be able to pay for itself 'with costs not exceeding benefits' (Balkema et al., 2002). Carvalho et al. (2009) discusses 'cost recovery' as an indicator, but in their case, the cost recovery was connected to illegal connections, and lost taxation. Muga and Mihelcic (2008) expressed that energy recovery would aid in avoiding the use of fossil fuels, and they also recommended future studies to make use of energy production in the sustainability valuation of technologies. Similarly, Singhirunnuson and Stenstrom (2009) discussed the benefits of resource recovery, but they did not include the possible revenue, that could come from it. Since wastewater infrastructure is publicly owned, it is a major shift in approach to consider public infrastructure as a financially profitable investment (Morales and Oberg, 2012). Depending on the needs of individual municipalities, revenues could be attained through water reclamation, the sale of biosolids or energy sales. Energy can be produced through heat exchangers, and the biogas can be produced from anaerobic technologies (Noyola et al., 2006).

Environmental

Quality of Effluent

Measure: percentage of BOD5, TSS, N and P removal

Directionality: Higher percentage removal indicates higher performance

Most researchers evaluate the quality of the effluent through different measures. Lindholm et al. (2007) uses 10 different measures to describe the quality of the effluent. Kholghi (2001), only expressed the quality of effluent using a ratio of 0 – 1. Using Biochemical Oxygen Demand (BOD) as an indicator for the quality of effluent is common in WWTP analyses (Bengtsson et al., 1997; Lundin et al., 1999; Mels et al., 1999; Hellstrom et al., 2000; Anagnostopoulous et al., 2007; Lindholm et al., 2007). Additionally, the Commission on Sustainable Development (2001) recognized BOD as a vital measure for testing wastewater quality. Biochemical Oxygen Demand is the quantity of oxygen in milligrams per liter used in the degradation and oxidation of organic and inorganic material. TSS, next to BOD is the most commonly seen component used to judge the performance of a WWTP. TSS stands for Total Suspended Solids and it is also measured in mg/l. Nitrogen (N) and Phosphorous (P) removal are also vital in dictating the quality of the effluent. Though these nutrients are vital to all living beings, the high concentration of N and P are found to be deadly to flora and fauna at WWTP outfalls (Metcalf and Eddy, 2003). Muga and Mihelcic (2008) also explain that the quality of effluent is an important indicator for understanding the effluent reuse *potential*. This consideration is significant especially in the Canadian context, where the high fresh water supply in many municipalities reduce the interest in immediate wastewater reuse (Fidelis, 2011). Regulations covering both issues have public health in mind In Canada these regulations, for both public and environmental health protection are present on both a Federal and Provincial level.

Quality of Biosolids

Measure: Pathogens and heavy metal content

Directionality: Higher quantity indicates a lower performance

Biosolids are processed biological sludge. Biosolids hold nutrients that are vital for healthy soil. If they are cleaned to an appropriately safe level, biosolids can be reused as a rich, organic fertilizer (Otterpohl et al., 1999). If they are processed and reused, they can assist in the phasing out of land-fills as well as the reduction of incineration (Apedaile, 2001; Amajirionwu et al., 2008). Land-filling especially is both an expensive, and an environmentally unfriendly process. Municipalities throughout Canada are attempting to avoid this alternative (MV-SF, 2010). Due to the many hundreds of thousands of tons of biosolids produced in countries all over the world, many researchers have found that 'biosolids' or 'sludge' are helpful components in the ranking of the sustainability of WWTPs (Bengsson et al. 1997; Emmerson et al., 1995;

Lundin et al., 1999; Mels et al., 1999; Lundin and Morrison, 2002). Kaerrmann (2001) even claimed that nutrient and heavy metal control are the most important components of a cleaning technology. Heavy metal accumulation in soil, plants, and animals depends on the species (Mattioni et al., 1997). High concentrations can be dangerous for human health (Pasquini, 2006). Depending on the type of secondary technology used to produce the biosolids produced can differ, yielding different levels of nutritional values, as well as various safety levels in their reuse. Biosolids are especially important in the discussion of resource recovery and reuse.

GHG emissions

Measure: Carbon Dioxide and Methane output metric tons/day

Directionality: A lower output indicates higher performance

Depending on the secondary treatment used, many types of WWTP produce methane (CH_4) and nitrous oxide (N_2O), which are 21 and 310 times more potent than Carbon Dioxide (CO_2) (AAEE, 2008) and thus they can contribute to accelerated GHG output and to climate change (UNEP and UN-Habitat, 2008). The IPCC (2007) predicted that there would be a 50% increase in methane production from world-wide wastewater and wastewater management between 1990 and 2020. In British Columbia there is a climate action plan to reduce GHG 33% by 2012, based on 2006 levels, and over 80% below by 2050 (ILWTP, 2010). WWTP generally are very energy intensive processes due to heating and pumping needs, water treatment systems are thought to 'consume' 3% of the US energy resources (Zimmerman, 2004). Van der Kreijf (2007) believed that there was a pressing need to minimize the production of GHG and to have more efficient technologies to reduce the need for fossil-fuel energy. Especially in North America, there are numerous opportunities to increase the energy efficiency of the WWTPs (Muga and Mihelcic 2008). WWTPs that use recycled materials and incorporate energy production have the capability of decreasing GHG output significantly.

Land Use

Measure: Land area required for technology

Directionality: A lower land area needed indicates a higher performance

Land use has previously been used in WWTP selection studies (Ellis and Tang, 1991; Anagnostopoulos et al., 2007; Zeng et al., 2007; Dabaghian et al., 2008; Fidelis, 2011). In the 2003 study by Dixon et al. 'Land use' was categorized under the criterion 'Environment'. In Metro Vancouver just like in many other Canadian municipalities, land is expensive, (Morales and Oberg, 2012). Due to its many other potential uses (eg. residences, industry, and nature), it is in the best interest of most municipalities to select more compact technologies. Though all the secondary treatment technologies are space-saving alternatives, they all have varying land area needs in order to function.

Social

Aesthetics

Measure: Number of complaints about odor, construction or visual appeal (whether justified or not)

Directionality: More complaints indicates a lower performance

Societies have been known to stand their ground in situations where the environment was not being considered and/or something was 'unfair' (Nancarrow et al., 2003). Though societies are known to be concerned about taxes, social sustainability or social acceptance cannot always be won through lower cost technologies. Especially, in space-constrained municipalities, wastewater infrastructure is located closer to the public thus making residents more sensitive to the infrastructure. Public participation was found to be a vital component in making decisions in both peer-reviewed literature, (Muga and Mihelcic, 2008; Singhirrusorn and Stenstrom, 2009) and by various levels of the government (BC, 1999; MV-SF, 2010). For a system to be both democratic and sustainable, the perspectives of the public must be taken into consideration. ‘Aesthetics’ was used as a ‘social’ indicator. ‘Aesthetics’ has been used as an indicator in a number of studies (Berndsson and Jinno, 2006; Muga and Mihelcic, 2008). Most centralized WWTPs in municipalities are located away from populated areas (Jantrana and Gross, 2006). Being close to residences increases the ‘undesirability’ of infrastructure (Tuzkaya et al., 2008). Though industrial infrastructure is not expected to be ‘beautiful’ (Aragones-Beltran et al., 2010), low aesthetic performance has led to deterioration of comfort and discouraged investment in the local housing market (Metcalf and Eddy, 2003).

Odor is commonly seen as the largest concern by residents (Metcalf and Eddy, 2003) and in come cases, WWTP projects have been rejected by the public primarily due to odor fears (Anagnostopoulos et al., 2007). A variety of WWTP technology selection studies include odor as a component of their analysis (Anagnostopoulos et al., 2007; Lindholm et al., 2007; Berndtsson and Jinno, 2008; Dabaghian et al., 2008; Bottero et al., 2011). Lindholm et al. (2007) included an indicator measuring ‘noise by increased traffic’ and ‘risks by increased heavy lorries’. Anagnostopoulos et al. (2007) included ‘construction’ in their study but did not include any measurements.

Balkema et al. (2002) expressed that social and cultural indicators are generally difficult to quantify, and few papers offer specific measures of their indicators. In Berndstsson and Jinno’s (2008) and Bottero et al. (2011), the terms ‘No’ and ‘Yes’ were used to describe ‘odor’, but neither identified the significance of the scores. In the 1996 study in Seattle, Keeney et al. measured all inconveniences from disruptions, odors, noises, visual impacts, and traffic in ‘person-years’ of each impact. The Greek study by Anagnostopoulous et al. (2007) suggested more objective and scientific olfactory meters to test for odor thresholds. The paper, recognizes that objectivity is difficult because people ‘do not respond in the same way’ to odors (Anagnostopoulous et al., 2007).

Cultural Acceptance

Measure: Cultural and religious comfort experienced by society

Directionality: Higher comfort indicates a higher performance

Agenda 21 (1992) expressed that part of sustainable development was the inclusion of aboriginal and minority groups’ rights; British Columbia, has recently started a campaign to increase First Nations engagement. Additionally, Ellis and Tang, (1991) and Mead et al. (2007) express the need to consider general cultural desires as society as a whole can be very diverse. Under the criterion *Social*, all of society has been included. Various researchers have expressed that cultural/religious concerns cannot be ignored in the development of urban water systems (Ellis and Tang, 1991; Mead et al., 2007).

Perceived Safety

Measure: the public’s perceived safety

Directionality: the higher the perceived safety the better

Societal safety and health are considered issues of primary importance by every level of the Canadian government as well as by numerous researchers of WWTP technologies (BC, 1999; CCME, 2009; Sahely et al., 2005, Dabaghian et al., 2008). Lundin and Morrison (2002) claim that in the developed world, large scale centralized systems are successful at protecting health and safety of citizens. As the technologies are all capable of providing high levels of human safety, in this Canadian study, safety was measured through *perception*. Perceptions of risk and fairness are believed to be important components of personal values of a community, according to a model by Nancarrow et al. (2010). People should *feel* comfortable and safe in their environment. At times the public is not knowledgeable making them have ‘unreasonable fears and expectations’ (Dietz et al., 1989). Different technologies have different impacts on how safe people feel (Midden and Huijits, 2009). In a study done in Tehran, Iran, by Dabaghian et al. (2008) it was found that the indicator ‘Safety’ lead to some of the widest variation of weights between consultants and engineers. Dabaghian et al. (2008) have not discussed the measure or the type of safety features used, however, an indicator considered contentious in one situation may lead to interesting discussions in other case studies.

Technical

Flexibility

Measure: Ability to perform at desired level regardless of potential future climate change, expansion requirements or unexpected loading

Directionality: Higher adaptive capabilities indicate a higher performance

Metcalf and Eddy (2003) described efficiency and reliability as some of the most important engineering components. Efficiency of the WWTP seen in Sahely et al. (2005), Muga and Michlcic (2008) and others, was not organized under the technical criterion, as the efficiency of the treatment process can be seen in the quality of the effluent and biosolids under the ‘Environmental’ criterion.

The indicator ‘Flexibility’ has been considered one of the most significant indicators when approaching the issue of sustainability (Sahely et al., 2005; Berndtsson and Jinno, 2006). This is similar to Amajirionwu et al. (2007) who expressed that flexibility should in fact ‘encompass’ each criteria making up the triple-bottom-line. Infrastructural establishments in municipalities are meant to last for decades (Sahely et al., 2005; Lundin and Morrison, 2002) however, municipalities themselves are always changing. A system that is flexible is most likely to adhere to the uncertainty of the changes embedded in considering 'future' during sustainability analyses (Larsen and Gujer, 1997). Climate change can have an impact on the performance of a WWTP, as different technologies have different optimum temperatures (Metcalf and Eddy, 2003). Increased water levels due to climate change are also a potential problem for WWTPs, which are usually located on the shores of bodies of water. Sahely et al. (2005) uses both the indicators *Flexibility* and *Adaptability*, however with the use of Larsen and Gujer's terminology, the indicators can be seen to represent the same concept. For the North Shore case study, three particular issues of uncertainty were included according to recommendations by Muga and Michelcic (2008), flooding from climate change, expansion requirements from population growth of the North Shore and new influent qualities.

Reliability

Measure: Risk of failure

Directionality: Low risk of failure represents high reliability which indicates a higher performance

Sperling (1996) believed that in the developed world *Reliability* along with a few other components are critical over 'affordability'. Singhirrunnusorn and Stenstrom (2009) and Loucks (1997) presented 'reliability' as covering both short and long-term mechanical reliability. The *Reliability* indicator under the criterion *Technical* represents the risk of failure. If there is a low risk of failure then there is higher reliability allowing for an understanding if that quality of performance can be trusted for a specific period of time under specific conditions. Reliability measured alongside flexibility can be useful for understanding the performance of the technology

(Kholgi, 2001). Hellstrom and Kaerremann (2000) also used a term connected to reliability as an equivalent to a risk analysis. The 'reliability' indicator will aid in differentiating new and innovative technologies from older technologies. Newer technologies may prove functional, and they may incorporate new ideas, however, there is less reliability if there are not many examples of their long-term use. Reliability indicates the risk factors of a technology. Reliability decreases as a potential, and consequence of failure increases (Metcalf and Eddy, 2003).

Simplicity

Measure: The ease of construction, operation and maintenance of the technology

Directionality: Increased simplicity indicates a higher performance

In discussing the complexity of the technology itself a variety of indicators have been used. Balkema (2002) used 'Expertise'. Fidelis (2011) and Singhirussorn and Stenstrom (2009) used the term 'Complexity', while Dabaghian et al. (2008) used 'High technology' as an indicator to identify the varying levels of engineering ability required to run and repair the secondary treatment plant alternatives. In a comparison of indicator weights, Dabaghian et al. (2008) found 'high technology' was the indicator with the highest score variations. This is similar to Singhirussorn and Stenstrom (2009) who found their experts ranking showed this indicator to be the most controversial within their indicator selection. This component has been considered particularly important in the developing world (Ellis and Tang, 1991), where education and skills of labor force may not be able to facilitate the complexities of maintenance and operations of advanced technologies (Bdour et al., 2008). Even in the developed world, however, more complex technologies require increased time and finances in training, and 'poor operator understanding' can frequently cause problems at WWTPs (Muga and Mihelcic, 2008) and high turnover of operators can make special training ineffective (Mallett, 2007).

Appendix I

Interviews

Galal, Hana (Interviewer) and Operations Supervisor. (June 28, 2012). Oral Interview [Interview Transcript].

Galal, Hana (Interviewer) and Municipal Manager. (July 24, 2012). Oral Interview [Interview Transcript].

Galal, Hana (Interviewer) and Provincial Consultant. (August 16, 2012). Oral Interview [Interview Transcript].

Galal, Hana (Interviewer) and Provincial Decision Maker. (August 17, 2012). Oral Interview [Interview Transcript].

Galal, Hana (Interviewer) and Academic/Consultant (August, 23 2012). Oral Interview [Interview Transcript].