A Customer-driven Decision Making Framework for Drinking Water Systems

Ahmed Serag

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Signed by the final examining committee:

Dr. Z. Zhu ______ Chair

Dr. W. Hamouda ______ Examiner

Dr. F. Nasiri ______ Examiner

Dr. T. Zayed ______ Supervisor

Approved by ______
Chair of Department or Graduate Program Director

______
Dean of Faculty

Date ______

Abstract

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According to the 2013 ASCE infrastructure report card, the USA potable water system needs an investment of $384.2 billion over the next 20 years to meet current and future needs. The American infrastructure, which has a GPA of D+ and rated as poor, needs an investment of $3.6 trillion for all infrastructure assets by 2020. One of the key proposed solutions was to prioritize the maintenance of infrastructure considering the Level of Service (LOS). Most of research works on water distribution network (WDN) focused on the condition or performance of water systems creating a gap between municipal goals and public expectations. It is evident that there is a lack of research in the area of LOS and its link with WDN condition. There is a vital need in municipalities to link renewal plans with the Level of Service. Therefore, the main objectives of the present research are to: 1) identify and study the factors that impact the LOS, 2) establish an assessment model for LOS in the WDN, and 3) map the LOS to WDN condition.

Building upon recent work on the LOS of drinking water supply systems, the present research identifies LOS factors based on the review of water supply system (WSS) performance indicators from literature and experts in the domain. It consequently develops a framework that is dependent on two main models: (1) Best-Worst Method (BWM) model that determines the LOS of a WSS considering the relative weight of importance of the identified LOS factors and (2) Artificial Neural Network (ANN) model that maps the WDN condition to LOS. Using the water network data set of the city of Montreal, the framework is tested and the impact of pipe material and environmental conditions on breakage rate is studied. This research proves that breakage rate varies significantly for different pipe materials and neighborhood areas with different environmental conditions. Questionnaire responses from the industry experts show that supply pressure and continuity, quality of supplied water, and customer complaints are the main factors that govern the quality of service. They also show that water quality is the most important factor to the LOS among the other significant factors. The relationship between WDN condition and LOS is determined considering the metrics of water quality, customer complaints, as well as pressure and continuity of water supply. An Artificial Neural Networks (ANN) model is developed in which the above metrics are considered the input variables and the LOS total score resulting from the developed BWM model is the output variable. The model is cross-validated using the embedded validation in the used software resulting in an R2 value of 0.871, which reflects a good representation of the relationship between the inputs and the outputs. Municipal management teams will be able to connect the technical world of condition assessment of WDN to the customer world by adopting a customer-oriented decision making process. This enables them to understand the customer perception of the provided service, optimize the budget allocation process and forecast the LOS based on the network condition. It also opens perspectives to key issues for future research work to diagnose the customer perception of municipal infrastructure performance.

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Chapter I

INTRODUCTION

The provision of safe and reliable water utility services is the main goal for municipalities in their scope of services Berg and Danilenko (2011). Therefore, research, municipal and governmental plans have the provision of drinking water service at their core. Not only developing countries find it imperative to improve municipal performance in this sector; developed countries also need to surmount all the challenges that face their infrastructure assets, including the challenge of water assets deterioration. A number of those major challenges are as follows:

- The growing pressure on these utilities, due to wear-out, and the needs generated by demographic changes, i.e. population growth and migration adaptations,
- The rising demand for higher environmental and societal sustainability standards,
- Climate change uncertainties.

According to the ASCE (2013) report card, the need for investment in municipal water assets in the United States is increasing dramatically due to wear-out and population growth as shown in Figure I.1. Most of the investment needs for both the Northeast and Midwest of the US were going towards the replacement of old or deteriorating assets with \$92 million and \$147 million, respectively, needed for these replacements and then comes investments needed to meet future demands with \$17 million and \$25 million, respectively. Most of the South and the West needed investments are going towards meeting future demands with \$303 million and \$154 million, respectively, furthermore, $204 million and $83 million, respectively, are needed for replacements. This has led the AWWA to consider the rise of household water bills in its recommendations in order to meet the investment costs in water infrastructure; This also means more customer involvement.

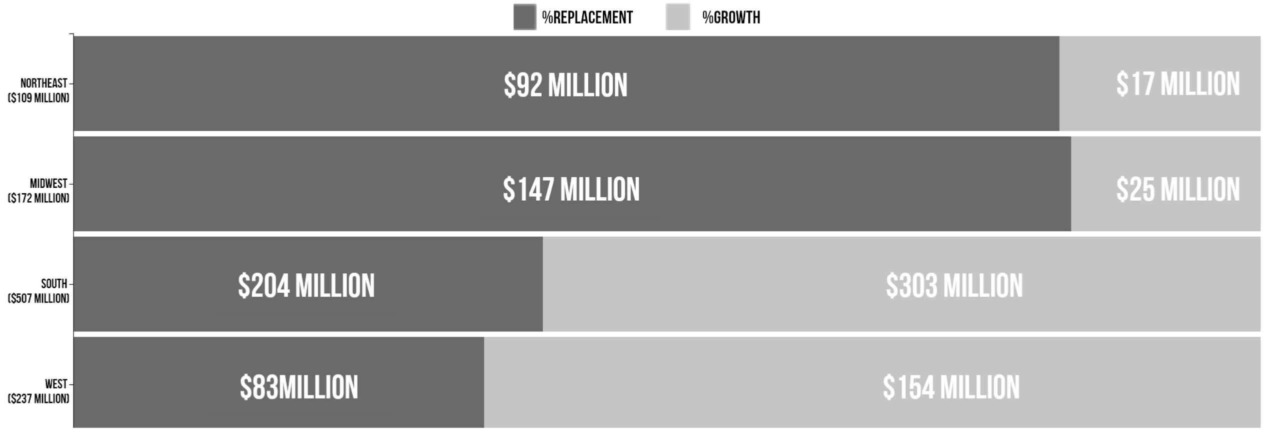

Figure I.1: Investment Needs for Drinking Water Mains by Region (2011 - 2035)

Despite the fact that the core function of urban water facilities is to deliver water as a physical product, drinking water delivery should be defined as a service since customers - i.e. the public - only pay for the value added by the service, and not the ownership of water. This is because water always goes back to the environment through evaporation, drainage and/or sanitation systems (Prevos 2016). The fact that condition impacts level of service can appear clearly when a direct degradation of water quality happens because of leaks in water pipes because of contaminants entering the pipe through leak cracks in cases of pressure loss (Hunaidi 2000); Corrosion fragments also get mixed into th water which causes health risks. This thesis builds upon recent work in the synthesis of customer-driven infrastructure asset management and demonstrates the feasibility of defining the level of water service for a municipality. Using Montreal drinking water network as an example, this research builds an index framework for the Level of Service and identifies the relationship between the utility and customer perception of the Level of Service. The remainder of this chapter elaborates on the motivations of this research, presents its specific objectives and the adopted approach, and outlines the structure of this work.

I.1 Motivation

According to the Canadian Infrastructure Report (2016), the current water infrastructure reinvestment levels, i.e. 0.9% for the linear assets and 1.1% for the non-linear assets, will result in a decline in the condition of potable water assets over time. Thus, higher levels of investments are needed to maintain and improve the conditions of current assets especially in preventive maintenance as a major consideration for saving money in the long run. Preventive maintenance can handle costly reconstruction and service disruption. According to the American Society of Civil Engineers (ASCE) report (2013), there are 240,000 water main breaks per year in the US and the current investment levels are not sufficient to sustain proper levels of potable water service provision.

The main goal of the infrastructure asset management has always been to sustain infrastructure assets performance in order to provide the public with the promised service. Communicating water system performance to the public is a challenging task since most utility providers do not have a clear understanding of how the non-expert audience perceive the improvement or decline in a water system performance. Drinking water industry, if we may call it as such, has a monopolistic nature due to the economics of scale. That is why the maximum efficiency can only be achieved by depending on one single provider (DiLorenzo 1996). Thus, the customer cannot change the provider unless there is a clear violation of health standards or defection. Consequently, the consumer element has been added to the equation by the so-called 'yard-stick competition', where different utility providers are compared in terms of their service provision performance in similar markets (Braadbaart 2007).This has created the need for the development of a framework that helps asset managers quantify the amount of required improvement or rehabilitation to boost the Level of Service for a water network.

I.1.1 Problem Statement

There is a need to develop an a model that assesses the level of service of the water supply system, considering different factors that covers all aspects of water service, and deciphering LOS by putting it into context with water networks condition in the same framework.

I.2 Objectives

This research introduces a framework that describes the ongoing relationship between Water Distribution Network (WDN) condition and Water Supply System (WSS) Level of Service (LOS) in order to narrow the gap between the utility providers' goals and customer aspirations. More specifically, this thesis seeks to fulfill the following objectives:

- To study current practices in municipal asset management with a focus on issues related to service provision quality referred here as the Level of Service (LOS).
- To identify the factors that govern LOS covering all aspects of the customer or the public perception of drinking water service.
- To develop an LOS assessment model.
- To map LOS to the condition of WDN.

I.3 Brief Methodology

This study develops the methodology in the following steps:

- The identification of the Level of Service factors addressing all aspects of municipal water assets performance metrics, related to service provisioning and choosing the best group of indicators that form a comprehensive scheme reflecting the quality of the service,
- Weight calculation using the Best-Worst Method (BWM) of the chosen group of factors where each relative weight reflects how important the factor is with respect to the whole notion of the Level of Service,
- Mapping Water Supply System (WSS) Level of Service (LOS) to Water Distribution Network (WDN) condition using Artificial Neural Networks (ANN) where water distribution network metrics are the input variables and the Level of Service total score resulting from the developed model is the output variable.

As a result of the overall framework development, several areas of further investigation are also pointed out, for asset management researchers' consideration.

I.4 Thesis Organization

Chapter II presents a detailed literature review bringing the following areas into focus: Condition assessment, Multi-Criteria Decision Making (MCDM) to review Analytical Hierarchy Process (AHP) and Best-Worst Method (BWM), Water Supply System (WSS) service quality models, LOS constituent factors and Artificial Neural Networks.

Chapter III describes the research methodology in this study. It includes literature review, factors identification, the procedure to obtain the weights of service quality factors and the overall LOS score for Water Supply Systems (WSS) using BWM and the procedure of mappingLOS to Water Distribution Network's Condition using Artificial Neural Networks (ANN).

Chapter IV presents the data collection process and the collected data analysis and makes several conclusions regarding the relationships between several variables that exist in the collected data.

Chapter V describes the detailed procedure of developing the research framework by implementing as the survey results into the BWM model. This is to acquire the relative weights of the chosen factors using EVOLOVER® tool for optimization and then using the collected data for the ANN mapping process where Visual Gene Developer®® software was used.

Finally, Chapter VI reflects on the findings of this project and presents its limitations and recommendations.

Chapter II

LITERATURE REVIEW

Water Supply Systems (WSS) condition assessment and level of service models were reviewed separately due to the tremendous difference in the two. Focus was also kept on topics like performance indicators adopted in these different models, availability of data, service quality models in the world of business, multi-criteria decision making techniques and machine learning.

II.1 A Condition Assessment Strategy for Water Utilities

Infrastructure studies which were undertaken in the United Kingdom, Australia and the United States showed a common cause for concern which is the widespread deterioration of critical water and wastewater infrastructure assets, that is faced by insufficient renewal/replacement investment with the goal to ensure that water and wastewater utilities are capable of delivering sustainable services to the public. For example, according to the American Society of Civil Engineers ASCE (2013), a grade of D+ was assigned to US infrastructure which reflects a “poor” rating and only one grade higher than “inadequate/ failing” rating. The consequences in -terms of cost- of continuing with a poorly structured replacement/renewal regime could be dramatic. That can be seen in the United States based Water Infrastructure Network where it was estimated that the gap between spending levels and the investment needed to meet the United States’ national environmental and public health priorities embodied in its Clean Water Act and Safe Drinking Water Act is reaching US$23 billion a year over the next 20 years. Water and wastewater utilities in developed countries face challenge of how to be more cost effective with their physical assets while providing safe and reliable services to their customers. A Strategic approach is believed to help utilities overcome that challenge. A key element of that approach is the assessment of asset condition and performance. It provides some condition assessment tools that help improve the long-term planning and day-to-day management of assets.

II.1.1 Service-driven approach advantages

Recently, asset management approaches are getting more and more sophisticated where each successive approach is built on the previous one(s) as follows:

- Condition-based asset management
- Performance-based asset management
- Service-based (service level driven) asset management
- Risk-based asset management

In **Condition-based asset management**, spending is targeted towards maintaining assets condition, which is the approach adopted by most of engineers. Basically, if the condition is measured to be poor, the asset will consequently need maintenance/investment to rectify defects. In a similar fashion, **Performance-based asset management** focuses on 'what/how assets are doing?' in a local sense and the imposed question here is 'whether the asset is doing the job intended to or not?'. Again this approach is considered natural for engineers to manage assets. Towards a more customer-focused approach, **Service-based asset management** doesn't look at performance locally (the design intent of individual assets), but it digs deeper in the asset-management process reaching the customer level. Here, the question posed is ‘does the asset contribute (appropriately) to the service delivery?’ and it’s posed independently of its condition or performance relative to the design intent. **Service-based asset management** main goal to maintain the promised or at least minimum levels of service provided by the asset whether it’s on the local or regional level. The challenge here is that approach is less intuitive to engineers since sometimes it means that maintenance/investment won’t be to restore asset appropriate condition or even poor performing assets where the impact on service is acceptable. **Risk-based asset management** targets optimization of assets life cycle by considering risks of service provision where risk is defined as the product of ‘probability of failure’ and ‘consequence of failure’. Many factors contribute to the definition of risk including safety and the environment, customer expectations, reliability, efficiency and effectiveness, finance, reputation and regulatory relationships (Urquhart et al. 2007).

A sample of 30 survey respondents is shown in TableII.1, 21 of which were working in the Untied States and who responded to a web-based survey undertaken by Urquhart et al. (2007) where they were asked about what approach do they adopt among the aforementioned approaches, 29% of the respondents had no defined approach which meant the decision-making process wasn’t being conducted based on a well-structured and documented objectives, however, 28% of the respondents said that they were adopting the condition-based approach which was closer to the technical aspect of assets rehabilitation and condition assessment, performance-based approach came in third place followed by service-based and risk-based approaches.

Table II.1: Adopted Approaches to Asset Management

Asset management approach adopted	Proportion
Condition-based	28%
Performance-based	19%
Service-based	10%
Risk-based	14%
No defined strategy	29%

II.1.2 Strategic Goals and Performance Indicators

All utilities have aspirations (things to achieve) and imperatives (must-do things) which can be expressed in terms of business goals, which in turn reflects stakeholders' and customers' requirements. Utilities need KPIs to measure their performance and different types of KPIs are used as metrics to measure that performance including:

- Level of service KPIs
- Asset related KPIs
- Derived KPIs

The Level of service KPIs (e.g., customer complaints) are indirect measures of asset condition since it reflects the level of service as perceived by the customer or the environment and usually these KPIs work as a basis for asset management expenditure and prioritization processes. **Asset related KPIs** (e.g., pipe failures) are directly related to asset condition or performance and they are used also as basis for asset management expenditure and prioritization processes. **Derived KPIs** (e.g., amount of rehabilitation and annual investment) do measure asset management efforts and they can give an idea about assets condition and performance and are strongly influenced by policy decisions and available budgets.

Performance Indicators

According to the Canadian Water and Wastewater Association (CWWA) a **Performance Indicator (PI)** is “a parameter or a value derived from other parameters, which provides information about the achievements of an activity, a process or an organization with a significance extending beyond that directly associated with the calculated value of the parameter itself. For example, the average number of liters of water supplied per person per day. Indicators are typically expressed as commensurate or non-commensurate ratios between the variables.” And these variables are generated by the analysis of a specific service that is performed. variables should be accurately-measurable with available equipment, staff, and funds; easily reproducible or comparable and when measured they should be referenced to the geographical area and the reference time of the study area; relate to the indicator to be developed. Simply, variables are the baseline data that builds the value of a PI (e.g., population served, number of connections, etc.) (CWWA 2009). Different PI systems around the world are reviewed in the following section.

International Water Association (IWA)

The IWA’s first edition was published in July 2000.The PI System was developed after working with international managers, practitioners, and researchers (Nurnberg 2001). It was created for benchmarking purposes in Europe then a study was presented which was conducted on (about 30 large-scale companies, 270 medium-and small-scale utilities, and about 20 bulk supply companies) in Germany and it was noticed that all of them are adopting different approaches and a lack of standardization existed where a (Performance Assessment) PA comparison cannot be undertaken, that’s why the use of IWA manual of best practices was recommended by the world water congress (Nurnberg 2001). The aforementioned concept of a layered pyramid is further illustrated in Figure

II.1, used where raw data are at the bottom of the pyramid and PIs are in the above layers. Alegre et al. (2006) created a PA system of 150 PIs in six categories (i.e., water resources, personnel, physical, operational, quality of service, and economic and financial) and each group is divided into sub-groups for further detailing (e.g., total personnel, personnel per main function, personnel qualification). These subgroups comprise PIs which can be calculated using several variables that use specific units like percentages and ratios, these variables are the baseline data elements which reflect different measurements or recorded values in specific units.

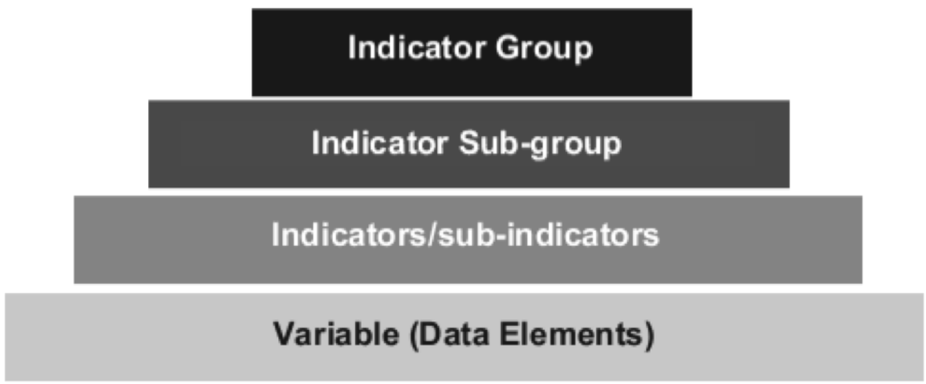

Figure II.1: Layer Pyramid by Alegre et al. (2006) for PIs Calculation

In 2006, IWA published its manual where 170 PIs were in the system, Figure II.2 shows an example for water resources and personnel categories, for example, the water resources category comprises two subgroups of Performance Indicators (PI) where each subgroup has two PIs. This system is well structured with wider applicability and it allows for a room to add future indicators and can be compared among different utilities. Water resources has two main indicator sub-groups which are (1) water resources availability and (2) usage efficiency and reuse. Under each of the two categories lies two performance indicators. Thus, making the total number of the performance indicators for the category water resources 4.

Indicator category	Indicator subgroup	Description of subgroups with number of PIs in each subgroup*	Total No. of PIs in each indicator category
Water resources	2	• Water resources availability (2) • Usage efficiency and reuse (2)	4
Personnel	7	• Personnel data (2) • Personnel per function (7) • Technical services personnel per activity (6) • Personnel qualification (3) • Personnel training (3) • Personnel health and safety (4) • Overtime work (1)	26

Figure II.2: A Part of IWA Manual of PIs for Water Supply Services

The World Bank

The energy and water department of the World Bank (WB) developed the International Benchmarking Network for Water and Sanitation Utilities (IBNET). It provides a set of tools for operational and financial performance assessment and through IBNET, water and sanitation utilities from all around the world including South Asia and Africa could compile and share their financial costs and PIs (Benson et al. 2012). The International Benchmarking Network for Water and Sanitation Utilities (IBNET) adopts a gradual approach where it provides a start-up kit" to move slowly towards a more advanced performance benchmarking system which can be useful for utilities in developing countries where there is a scarcity of data and resources. Despite that, it doesn't have as many indicators as IWA PA system. IBNET has 12 groups with 80 PIs and here in Figure II.3 (Process indicators and Service coverage) categories whose 19 and 3 indicators, respectively, are shown as an example. It is noticed that IBNET system is suitable for developing countries' utilities and that

Indicator category	Total No. of indicators	Performance indicators*
Process indicators	19	• Utility planning description (1) • Management of utility including training strategy, appraisal setting, etc. (5) • Higher management (1) • Types of financial resources (4) • Level of services offered by the utility (4) • Utility's procedures to assess customer satisfaction (4)
Service coverage	3	• Percentage of population covered with easy access (1) • Population coverage per household connection and per public point (2)

Figure II.3: IBNET System of Performance Indicators is because of the following features which makes it different from the IWA:

- Service coverage is a separate category since it's essential for most of developing countries where it's hard to deliver water,
- Water losses are taken up as a nonrevenue water,
- Network performance is represented by number of breaks per kilometers, on the other side IWA includes it into the operational category among other indicators, therefore, this indicator specifically reflects the structural failure of the water distribution system (WDS),
- The only mentioned physical component of WDS is (metering) but in IWA it's included with other indicators like pumping, valves, hydrants, treatment, and storage.

American Water Works Association (AWWA)

The American Water Works Association is the first drinking water organization in north America which was established in 1881. AWWA created a performance evaluation system that for WDS, where three categories existed: adequacy (quantity and quality), dependability(interruptions), and efficiency (utilization of resources) without including any PIs about targeting environment and water resources. In 2004 they launched the QualServe benchmarking program which is a PA system that enables comparisons for utility managers and lower level indicators can be added later to measure performance of each operational process of a water utility, 22 PIs were used, 17 of them are applicable to water supply and some of these PIs have sub-indicators totaling up to 35 indicators (Lafferty and Lauer 2005). The American Water Works Association (AWWA) divided PIs into 4 groups including organizational development, customer relations, business operations, and water operations. It was noticed after conducting several surveys that this System is suitable for benchmarking in North America. But still, environmental and water resources indicators have not been addressed.

The National Research Council of Canada (NRC)

The National Research Council of Canada developed a framework that is composed of 3 building blocks: objectives, assessment criteria, and the PIs. Six main objectives were identified public safety, public health, economy, environmental quality, social equity, and public security) (NRC 2010). PIs are assessed based on 11 assessment criteria which are also known as "indices" linking PIs to the aforementioned objectives. These assessment criteria are defined in the following:

- Safety Impacts: regarding accidents and incidents that result in death, injury or property loss because of water supply problems,
- Health Impacts: both direct and indirect, beneficial or detrimental.
- Security Impacts: both direct and indirect, beneficial or detrimental,
- Environmental Impacts: both direct and indirect impacts on natural environment (air, water, soil, fauna and flora) and climate change,
- Quality of Service: how well the service is meeting regulatory requirements, industry standards and customer satisfaction,
- Access to Service: infrastructure geo-coverage and affordability of services plus provision of access to people with disabilities,
- Adaptability: how adaptable is the service to short-and long-term changes and pressures ,

- Asset preservation, renewal and decommissioning (P/R/D): maintaining the LOS through inspection, routine maintenance, repair, rehabilitation, renewal and ultimately decommissioning.

- Reliability of service: ability of WSS to well-perform under stated conditions,

- Capacity to meet demand: capacity of the service to meet the required level under extreme events and in emergency situations.

It was noticed that the system is suitable for asset management at a strategic level and it needs to be supported with more PIs for practical PA system but generally it provides the most important and common factors (Husnain et al. 2014).

Evaluation of different PA systems

Several agencies developed PA systems which weren't mentioned in the document such as National Water Commission (NWC) in Australia, Office of the Water Services of Performance Indicators (OFWAT), Asian Development Bank (ADB) and Canadian Standards Association (CSA). Performance Indicators (PIs) categorization differs from an agency to another. For example, in IWA the operational group had water interruption indicator, whereas the same indicator was grouped into the customer relations category in the (AWWA). A comparison between the different categories has been made by Husnain et al. (2014) can be seen in Table II.2.

Table II.2: Number of WSS PIs Under Different Categories by Various Agencies

PI Category	WB	NRC	IWA	AWWA
Water resources/Environmental	11	25	4	-
Physical/Asset	1	-	15	-
Personnel/Staff	11	-	26	11
Water quality/Public Health	2	7	3	1
Operational	4	10	39	8
Quality of Service/Customer Service	17	8	34	2
Economic/Financial/Pricing	35	7	47	9
Total	**81**	**33**	**170**	**31**

Table II.2 shows seven PI categories and they are: (1) Water resources/ Environmental aspects, (2) Physical/Assets, (3) Personnel/Staff, (4) Water quality/Public Health, (5) Operational, (6) Quality of Service/Customer Service, and (7) Economic/Financial/Pricing. WB and IWA have the widest spectrum of PIs and cover all seven categories, whereas NRC and AWWA have a lesser spectrum by two categories and having five categories each. IWA has had the highest number of performance indicators for assessment at 170 performance indicators. On the other hand, AWWA has the least number of indicators at 31 indicators. It is clear that most PIs fall under finance, customer service or operation of WSSs, IWA has a broad range of indicators with 170 indicators, WB also has a fair number of PIs that covers all categories. On the other hand, the NRC system does not cover Physical assets status or Personnel categories. Water resources and Physical assets status categories are not covered in the AWWA system. Indicators terms vary across different agencies:

- In AWWA personnel/staff category is called organizational development, in WB 6 of the indicators are under process category and 5 under operating cost and staff category,
- Water Quality/Public health is categorized under quality of service in IWA and under water operations in AWWA,
- Three Operational Indicators were categorized under non-revenue water and 1 of pipe breaks

in WB; in NRC 6 of the indicators were under public health and 3 under economy; in IWA Water quality monitoring was considered under operational category; in AWWA water disruptions were categorized as customer relations indicator, system renewal rate was under business operations, water loss and structural integrity were under water operations,

- Nine of the quality of service indicators were under process category, 3 from service coverage and 5 from quality of service in WB; in NRC 4 were under public safety, 1 social equity and 3 public security,

- Economic indicators were distributed in AWWA amongst customer relations, business operations and water operations categories; in NRC 3 were under pricing indicators and 18 finance.

To evaluate the PI systems several criteria were indicated by Husnain et al. (2014) which were: (1) Understandability a PI should be easy to understand whether for utility managers or the public, (2) Measurability the data required to calculate the indicator should be easy to measure and the calculations themselves should be too, (3) Comparability a PI should be comparable whether locally or internationally across different utilities. Table II.3 shows a summary of the main findings of the research work in which the IWA system is considered the best PI system with a medium level of both understandability and measurability because the indicators chosen by the IWA are a clear reflection of the performance and most of the variables included are easy to measure for most of the utilities.

Table II.3: Evaluation of Different Performance Assessment Systems

Performance Assessment System	Performance Indicators		
	Understandability	Measurability	Comparability
WB	Medium	Medium	Low
NRC	Low	Medium	Low
IWA	Medium	Medium	High
AWWA	Low	Medium	Low

A high level of comparability is given to the IWA system because most well-known across the industry professionals which makes it easy for them to be compared across different geographies or utilities. The IWA system is noticed to be more balanced than most of PA systems with 170 PIs because of the following:

1. Performance Indicators (PIs) are distributed over all categories as compared to most of the other systems that lack that comprehensiveness,

2. Categorization of indicators into different levels which can adapt to different needs ranging from strategic managers who can start with level 1 to higher levels depending on data availability,

3. The way variables and PIs relate to each other provide means to utility and project managers to perform cross-comparison with similar sizes and types of utilities.

II.2 Multi-Criteria Decision Making (MCDM)

Multi-criteria decision-making (MCDM) or multiple-criteria decision analysis (MCDA) is categorized under operations research where multiple criteria are considered for decision-making. Because several conflicting criteria usually are involved in our daily lives while making decisions those criteria have to be evaluated.

The case study used in this research, different criteria/factors that constitute level of service for a WSS need to be evaluated with respect to the overall level of service factor. Considering multiple criteria leads to more complex problems but at the same time a more informed decision. There have been many advances in this field since MCDM discipline started in the early 1960s (Al-Dori et al. 2016). MCDM or MCDA has been useful for different domains, ranging from politics, business and economics to environment and energy. Typically, there is no optimal solutions for such problems because solving such problems is based on the decision maker's own preference or experience. and by solving it can mean: choosing the "best" alternative among different ones (where the "best" is the "the most preferred alternative" of the decision maker), choosing a set of good alternatives, or finding all "efficient" or "non-dominated" alternatives.

A feasible solution is non-dominated if it does not exist another feasible solution that improves an objective function without worsening at least one of the other objective functions (Clímaco et al. 2008). Therefore, a decision maker should choose a solution from the non-dominated solutions set. But if the decision maker was faced with a large number of non-dominated solutions he will have to trade-off certain criteria for others. Problems in MCDM are generally divided into two groups with respect to the solution space of the problem: continuous (where multi-objective decision-making MODM techniques are used) and discrete problems (which are solved using multi-attribute decision-making MADM) on which we are focusing here, MCDM is commonly used in the literature to refer to the discrete MCDM that's why we're using this term.

An MCDM problem is presented in the form of a matrix as shown in Figure II.4, where $\{a_1, a_2, .., a_n\}$ is a set of alternatives, $\{c_1, c_2, ..., c_m\}$ is a set of criteria and p_ij is the score of alternative i with respect to criterion j, Hence, the most important/desirable alternative is the one with the highest overall value (V_i) and it can be obtained by involving a weight for each criterion

W_j ($W_j \geq 0, \sum W_j = 1$) then V_i can be obtained using a simple additive weighted value function where the products of the alternatives scores and criteria weights are summed. This function is the underlying model for most MCDM methods, as in equation II.1:

$$Vi = \sum_{j=1}^{n} W_j P_{ij} \tag{II.1}$$

.

$$A = \begin{array}{c} \\ a_1 \\ a_2 \\ \vdots \\ a_m \end{array} \begin{array}{c} \begin{array}{cccc} c_1 & c_2 & \cdots & c_n \end{array} \\ \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mn} \end{pmatrix} \end{array}$$

Figure II.4: MCDM Problem Matrix

Several MCDM methods have been developed in order to calculate the weights or vector w=$\{w_1, w_2, ..., w_n\}$ and the most popular one is AHP (Analytic Hierarchy Process), ANP (Analytic Network Process), TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), VIKOR, and PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations). Many research studies worked on the comparison of MCDM methods (Adams 2003; Opricovic and Tzeng 2007; Wallenius et al. 2008; Zanakis et al. 1998).

II.2.1 Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process (AHP) is an easy technique that stimulates human decision process. It was developed by (Saaty 2008) more than 20 years ago and it assists decision makers in solving complex problems by guiding them through a sequence of pair-wise comparison judgments .A hierarchical structure is formed and it represents the relationships of the goals, criteria, sub-objectives and alternatives (outputs). AHP has been used in many disciplines, in planning and resource allocation, in conflict resolution and in prediction problems (Saaty 2008). Based on three principles (1) constructing hierarchies, (2) establishing priorities and (3) logical consistency, problems can be analytically solved (Saaty 2008). These principles are emphasized in several steps towards the determination of alternatives relative weights with respect to the existing criteria/factors. These steps are:

1. Setting up the Hierarchy
2. Pairwise comparison Matrices
3. Assigning Priorities
4. Establish Priority Vector
5. Logical Consistency Calculation
6. Combining Priority Weights

II.2.2 Best-Worst Method (BWM)

Pairwise comparison is a method that was developed by Thurstone (1927) under *the law of comparative judgment* .It is a structured way to show the relative preferences of several actions when it's not feasible to provide estimates for the actions with respect to criteria. For example, in AHP weight are derived from pairwise comparisons of alternatives against the criteria . In a pairwise comparison of n criteria by using a 1/9 to 9 scale, a matrix is obtained. In this matrix, a_{ij} shows the relative preference of criterion i to criterion j . When i and j are equally important $a_{ij} = 1$, whereas an extremely larger importance is shown by $a_{ij} = 9$. The matrix must be reciprocal, which means that for all i and j ,$a_{ij} = 1/a_{ij}$ and $a_{ii} = 1$. In order to obtain a completed matrix, it is necessary to have n(n-1)/2 pairwise comparisons. The matrix is consistent for each i and j, $a_{ik} * a_{kj} = a_{ij}$. The main challenge of pairwise comparisons is the lack of consistency which happens in practice (Herman and Koczkodaj 1996). The pairwise comparison matrix=(a_ij) will be perfectly consistent when, for each i and j, $a_{ik} * a_{kj} = a_{ij}$ .Unfortunately, because of (lack of concentration and several other reasons) inconsistencies occur most of the time and revision is then recommended. Rezaei (2015)developed a new MCDM method to overcome the shortcoming of the inconsistency of existing methods where fewer comparison data is needed. When executing a pairwise comparison in BWM. First, the best and worst criteria are chosen, which will be compared to the remaining criteria which lead to less comparison data. Figure II.5 shows the pairwise comparison between the best criterion to the other criteria and the other criteria to the worst criterion j. The author also demonstrated the performance of BWM by comparing with AHP which is claimed to be the most popular MCDM method and it was found that BWM performs significantly better than AHP in terms of consistency which will be explained later through an experimental case study which compares AHP to BWM in terms of how consistent are the answers derived from the questionnaire are.

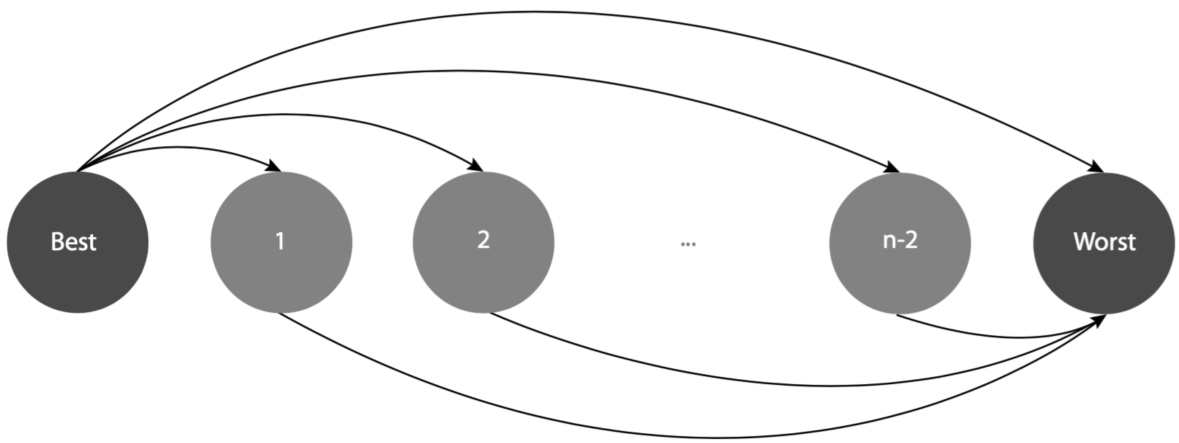

Figure II.5: Best-Worst Method Comparisons

Steps of BWM

According to Rezaei (2015), the following are the BWM steps:

Step 1: Determine a set of decision criteria

First criteria set/$c_1, c_2, ..., c_n$/ is defined which will be used to make the decision .

Step 2: Choose the best and worst

In the second step, the decision-maker is asked to determine the best and worst criteria. No comparison is made in this step.

Step 3: Determine the preference best to others

In this step, the decision-maker is asked to indicate the preference of the best criterion over all the other criteria using a number between 1 and 9. The resulting vector $A_b = (a_{B1}, a_{B2}, ..., a_{Bn})$.

Step 4: Determine the preference others to worst

Here, the decision-maker is asked to indicate the preference of the other criteria over the worst criterion using a number between 1 and 9. The resulting vector is $A_w = (a_{1W}, a_{2W}, ...a_{nW})$.

Step 5: Find the optimal weights

The final step is to calculate the optimal weights for the criteria $(w_1^*, w_2^*, ..., w_n^*)$. The optimal weight for the criteria is where, for each pair of w_B/w_j and w_j/w_W, we have $w_B/w_j = a_{Bj}$ and $w_j/w_W = a_{jW}$.To satisfy these conditions, a solution must be found where the maximum absolute differences for $\left| \frac{w_B}{w_j} - a_{Bj} \right|$ and $\left| \frac{w_j}{w_W} - a_{jW} \right|$ for all j in minimized. Considering the non-negativity and sum condition for the weights, this result in the problem shown in Equation II.2:

$$\begin{aligned} min\ max\{ \left| \frac{w_B}{w_j} - a_{Bj} \right| , \left| \frac{w_j}{w_W} - a_{jW} \right| \} \\ s.t. \\ \sum_j w_j = 1 \\ w_j \geq 0, for\ all\ j \end{aligned} \tag{II.2}$$

The minmax function constructs an optimization problem which has two constraints: (1) the summation of all w_j weights should equals one and, (2) the weight w_j should be greater than or equal zero. The main objective in this problem is the minimization of the maximum value of the two parts of the problem which are: $\left| \frac{w_B}{w_j} - a_{Bj} \right|$ and $\left| \frac{w_j}{w_W} - a_{jW} \right|$.

In order to solve this problem it is transferred to the following mathematical programming problem as in Equation II.3:

$$\begin{aligned} & min\ \xi \\ & s.t. \\ & \left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \xi, for\ all\ j \\ & \left| \frac{w_j}{w_W} - a_{jW} \right| \leq \xi, for\ all\ j \\ & \sum_j w_j = 1 \\ & w_j \geq 0, for\ all\ j \end{aligned} \tag{II.3}$$

The goal of this mathematical problem is to minimize the value of ξ while satisfying three conditions which are: $\left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \xi$, $\left| \frac{w_j}{w_W} - a_{jW} \right| \leq \xi$ and that the summation of all weights $\sum_j w_j$ equals one. After solving the mathematical programming problem, the exact value of ξ^* is obtained.

Consistency Ratio

As previously mentioned, it is necessary to check for the consistency of pairwise comparisons.Consistency decreases when $a_{Bj} \times a_{jW}$ becomes higher or lower than a_{BW}, in otehr words, $a_{bj} \times a_{jW} \neq a_{BW}$, accordingly, the highest possible inequality exists when a_{Bj} and a_{jW} equals to a_{BW} which is the maximum value and that results in ξ. Thus, ξ is a value that should be subtracted from a_{Bj} and a_{jW} and added to a_{jW} which will result in equation II.4:

$$(a_{Bj} - \xi) \times (a_{jW} - \xi) = (a_{BW} + \xi) \tag{II.4}$$

In case of accounting for the minimum consistency, $a_{Bj} = a_{jW} = a_{BW}$, we have:

$$(a_{BW} - \xi) \times (a_{BW} - \xi) = (a_{BW} + \xi)$$
$$\xi^2 - (1 + 2a_{BW})\xi + (a_{BW}^2 - a_{BW}) = 0 \qquad \text{(II.5)}$$

Solving for different values of a_{BW}, the maximum possible ξ values are obtained as in Table II.4. Rezaei (2015) used the values in Table II.4 to calculate the consistency ratio.

Table II.4: Consistency Index Table

a_{BW}	1	2	3	4	5	6	7	8	9
Consistency Index (ξ max)	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Then, the Consistency Ratio can be calculated using Equation II.6 :

$$ConsistencyRatio = \frac{\xi^*}{Consistency\ Index\ (\xi max)} \qquad \text{(II.6)}$$

The consistency ratio is obtained by dividing the optimized objective value (ξ^*) resulting from solving Equation II.3 by the consistency index ξmax that is obtained from Table II.6 using a_{BW} values for each respondent. Consistency ratio reflects how consistent a respondent answers are where the higher the value is from zero the less consistent a respondent will be, meaning that, a full consistent respondent will result in a zero consistency ratio. In case of collecting data from more than one respondent, it is important to calculate the final value of the consistency ratio by averaging the ratios for each respondent.

AHP vs. BWM

In order to test BWM against AHP and intuitive decision-making, Rezaei (2015) used a case study about ”mobile phone selection” where a person wants to select a mobile phone using different criteria which were found by Işıklar and Büyüközkan (2007) to evaluate different alternatives. As shown in Table II.5, ranking of mobile phones was found to be the same for all methods. However, weights given to different criteria and consistency of each method was different. It was more interesting and important to evaluate the BWM performance and it was found that BWM performed better than AHP in terms of:

Table II.5: An Overview of The Case Study Results

		Final weights (n=46)				Consistency Ratio (CR) (n=322)
		Nokia Lumia 920	iPhone 5	Samsung Galaxy S III	Motorola Milestone 3	
BWM	Mean	0.1960	0.3619	0.3137	0.1284	0.3573*
	s.d.	0.0938	0.1208	0.1007	0.0742	0.2029
	Minimum	0.0498	0.1537	0.1260	0.0399	0.0000
	Maximum	0.4802	0.5703	0.5827	0.3321	1.0000
AHP	Mean	0.2057	0.3501	0.3086	0.1356	0.1367**
	s.d.	0.1124	0.1415	0.1231	0.0783	0.1749
	Minimum	0.0459	0.1010	0.0736	0.0359	0.0000
	Maximum	0.5100	0.6855	0.6226	0.3834	1.9392
Intuitive	Mean	0.2033	0.3620	0.3285	0.1063	
	s.d.	0.1208	0.1507	0.1121	0.0646	
	Minimum	0.0500	0.1000	0.1000	0.0100	
	Maximum	0.6000	0.7000	0.5500	0.3500	

* 57.8% of matrices have CR less than 0.1; 18.9% between 0.1 and 0.2; 14% between 0.2 and 0.3, and 9.3% greater than 0.3.

** 77.3% of vectors have CR less than 0.5, and 23.4% between 0.5 and 1.0.

- **Consistency of comparisons**, consistency was calculated for all respondents' comparisons, as can be seen from Table II.5, BWM always results in consistent comparisons (not necessarily full consistent) where 57.8% of matrices have CR less than 0.1; 18.9% between 0.1 and 0.2; 14% between 0.2 and 0.3, and 9.3% greater than 0.3.On the other hand, AHP comparisons are considered inconsistent if CR$\geq .1$ .Hence, 56.8% of the matrices of AHP were consistent .

- **Minimum violation**, which is a measure that checks for the ordinal consistency of an MCDM method, it penalizes order reversals or violations and BWM was proven to have a significant better ordinal consistency compared to AHP.

- **Total deviation**, which measures the actual euclidean distance between the ratios of weights wi/wj and their corresponding pairwise comparisons. BWM also performed better than AHP in terms of total deviaiton.

- **Conformity**, which is the conformity to other MCDM methods, or the intuitive rankings of the decision-makers. It measures the euclidean distance between final scores found by an MCDM method, and the intuitive scores. BWM resulted in final scores that are closer to the intuitive evaluation compared to AHP.

- **Time spent on filling the questionnaire**, for BWM (mean =16.8m,s.d.=5.4) which is significantly (p=.019) less than the time spent for filling the AHP questionnaire (mean=18.8m,s.d.=6.8).

To sum up, BWM provides a better representation of the perspective of the respondent of the relative importance of different potions or criteria and that is mainly because of having a shorter time to fill the questionnaire which results in higher accuracy and consistency. However, some techniques account for the range of inconsistency by providing an upper and lower limit for each weight as in Interval AHP technique. On the other hand, the technique is more complicated and still requires more time to fill its questionnaire.

II.3 A Value-Driven Asset Management System

Level of service reflects social and economic goals of the community and it is comprised of several parameters such as: customer satisfaction, reliability, and availability (Infraguide 2005). Few models, frameworks, and approaches were developed to reach a customer-driven asset management system for water networks to close the gap between communities and utilities and to reduce subjectivity in agencies decision making.

II.3.1 A Community-driven Framework (Khan 2014)

A community-driven framework was developed by Khan (2014) for sustainable municipal asset management where he addressed three municipal assets types i.e. roads, water distribution, and sewerage collection. Condition rating was mapped to the level of service to quantify the improvement needed and that is the part which will have the light shed on here. Figure II.6 shows a schematic of the model development.

The methodology went through several developments starting with:

1. **Scaling asset condition and performance**: where he determined suitable performance indicators and measures for different asset types, their thresholds, and desired values. Then, he distributed their ranges in levels of service from the community perspective. He also did the same for condition rating from the agency perspective. Khan (2014) used a scaling which was based on extensive review of literature in the domain and the best practices reported by platforms such as InfraGuide Canada and Federation of Canadian Municipalities (FCM). However, he recommended that every agency should develop its own scaling.

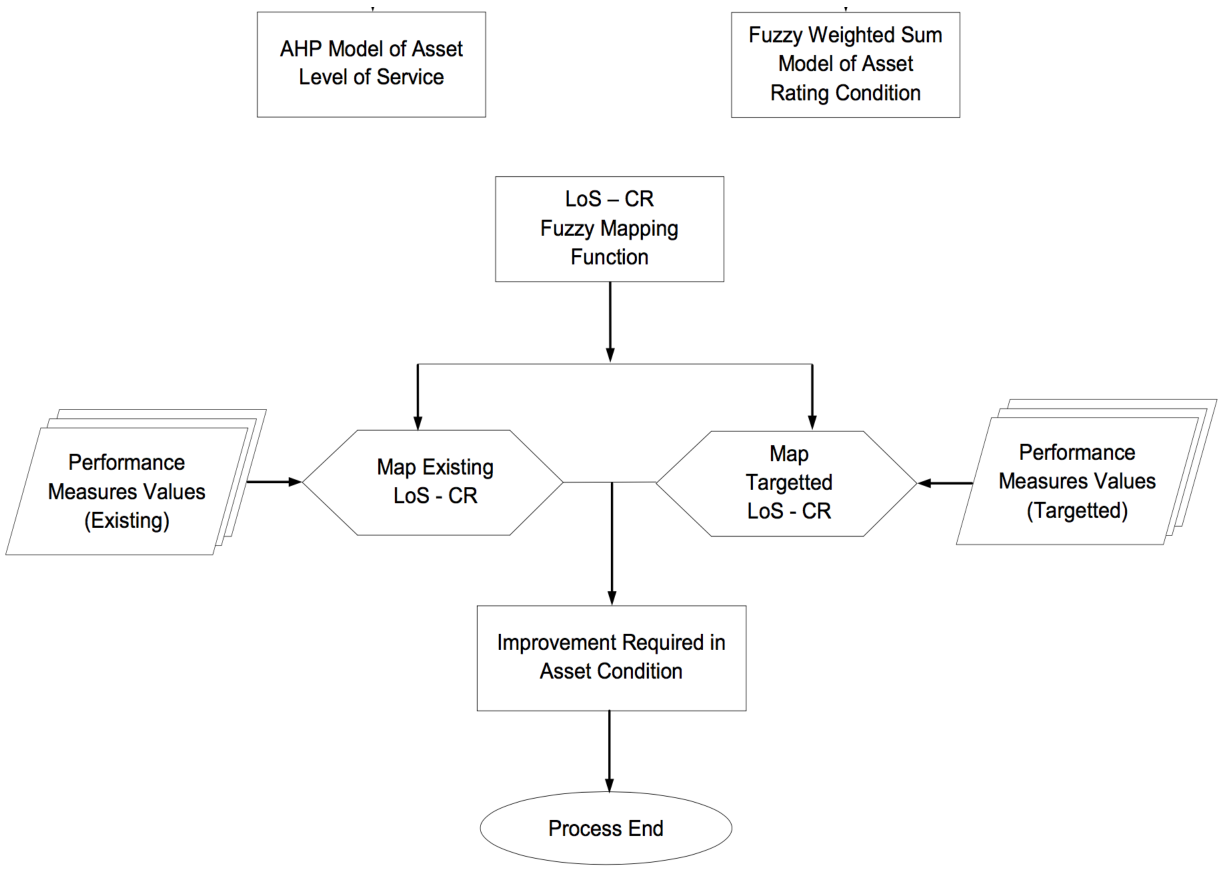

Figure II.6: Performance Modeling and Quantification of Condition Improvement

2. **Measurement and Quantification of the level of service**: AHP was used to measure and quantify LOS in terms of service points.

3. **Measurement and Quantification of Asset Condition**: Fuzzy weighted sum model was developed to measure and express asset condition.

4. **Mapping LOS to Asset Condition**: Fuzzy Alpha-cut theorem was implemented to use a mapping function that maps LOS to the corresponding condition of the asset so to quantify the improvement in asset condition, required to raise the level of service of the asset from the existing to the desired one as shown in Figure II.6.

Data Collection: Case Study, Riyadh Sub-network

The city of Riyadh (the capital of Saudi Arabia) was chosen to implement the methodology on. Data were collected from the community and the agency (e.g. inspection data, records, selections or choices from a set of options and making decisions based on preferences and needs). Data were collected regarding geographic co-ordinate's information of interconnected segments, information related to the selection of performance measures that constitute the level of service and condition rating with their grades, threshold, existing and targeted values of different assets as shown in Table II.6 and II.7. Every PI had different performance measures as in Table II.6; For example, structural PI has three measures: crack width, sag, and corrosion as a percentage of pipe thickness. Every measure was divided into five ranges of values that correspond to five levels of service, i.e. LOS1, LOS2, etc., where LOS1 is the highest level of service and LOS5 is the lowest. Failure thresholds are the minimum acceptable values of a performance measure, e.g. (1.0 mm) for crack width is the maximum allowed crack width. The existing and targeted value for each measure is also presented, e.g. Loss in water pressure current value is (25 Psi) and the targeted value is (15 Psi) which means that some action has to be taken despite not passing the threshold value, it does not achieve the targeted goal of that measure. Same approach was applied but with condition ratings as in Table II.7, meaning that, every performance measure range corresponded to a condition rating that ranges from (A to E), (none to extensive damage), where A is the best condition rating and E is the worst; For example, corrosion existing value is 60% reduction in pipe thickness which corresponds to a condition rating of D that is described as extensive.

Table II.6: Water Segment Performance Measures and Distribution of Its Values in Different Levels of Service

Performance Indicator	Performance Measure	Range of Performance Measure for Different Levels of Service (LoS)					Service Thresholds	Existing Value	Targeted Value
		LoS 1	LoS 2	LoS 3	LoS 4	LoS 5			
1	2	3	4	5	6	7	8	9	10
Structural	Fracture / Crack Width (mm)	0.0 - 0.10	0.11-0.25	0.26-0.75	0.76-1.25	1.26 -1.75	1.0	1.0	0.0
	Sag (≤ 0.1 D mm)	0-5	6 - 10	11-20	21-25	26-30	20	10	10
	Corrosion (% Pipe Thickness Reduction)	0-0	1-10	11-35	36-60	61-85	60	60	10
Operational	Leakage Volume (Litres/Day/Km/in-dia)	0-5	6-50	51-100	101-200	201-300	150	150	10
	Roughness Coefficient (C-Factor) Range= (175 - 25)	175 - 126	125 - 101	100 - 76	75 -51	50 - 25	65	65	105
	Loss in Water Pressure (Psi) Household Supply Standard = 60 psi	0-5	6-10	11-15	16-20	21-25	25	25	15
Water Quality	Lead Concentration (% Threshold) (Action Level at 10 % + ve Sample for 0.015 mg/l) Range= (0 - 100)	0.0-0.002	0.003-0.005	0.006-0.008	0.009-0.010	0.011-0.015	0.009	0.009	0.006
	Iron Concentration (% Threshold) (Action Level at 10 % + ve Sample for 0.3 mg/l) Range= (0 - 100)	0-0.1	0.11-0.15	0.16-0.2	0.21-0.30	0.31-0.5	0.25	0.3	0.15
	Total Coliform Bacteria (% positive samples in a month)	0.0-1.0	1.1-2.0	2.1-3.0	3.1-4.0	4.1-5.0	1	2	0

Table II.7: Water Segment Performance Measures and Distribution of its Values in Different Condition Ratings

Performance Indicator	Performance Measure	Value Type	Values of Performance Measures in Fuzzy Grades for Condition Rating					Service Thresholds	Existing	Target
			A	B	C	D	E			
1	2	3	4	5	6	7	8	9	10	11
Structural	Fracture / Crack Depth (mm)	Description	None	Negligible	Slight	Moderate	Extensive	Moderate	Moderate	None
		Value	≤ 0.0	≤ 0.15	≤ 0.50	≤ 1.0	≤ 1.5	≤ 1.0	≤ 1.0	≤ 0.0
	Sag (≤ 0.1 D mm) For 6" Ductile Pipe	Description	Nil	Very Slight	Slight	Moderate	Extensive	Extensive	Slight	Slight
		Value	≤ 0.0	≤ 5	≤ 10	≤ 15	≤ 20	≤ 20	≤ 10	≤ 10
	Corrosion (% Pipe Thickness Reduction)	Description	Nil	Slight	Moderate	Extensive	Severe	Extensive	Extensive	Slight
		Value	≤ 0.0	≤ 10	≤ 35	≤ 60	≤ 85	≤ 60	≤ 60	≤ 10
Operational	Leakage Volume (Litres/Day/Km/in-dia)	Description	Very Slight	Slight	Moderate	Extensive	Severe	Extensive	Extensive	Very Slight
		Value	≤ 10	≤ 50	≤ 75	≤ 150	≤ 250	≤ 150	≤ 150	≤ 10
	Roughness Coefficient (C-Factor) Range= (125 - 50)	Description	Very High	High	Moderate	Low	Very Low	Low	Low	High
		Value	≥ 125	≥ 105	≥ 85	≥ 65	≥ 50	≥ 65	≥ 65	≥ 105
	Loss in Water Pressure (Psi) Household Supply Standard = 60 psi	Description	Very Low	Low	Moderate	High	Very High	High	High	Low
		Value	≤ 10	≤ 15	≤ 20	≤ 25	≤ 30	≤ 25	≤ 25	≤ 15
Water Quality	Lead Concentration (Action Level at 10 % + ve Sample for 0.015 mg/l) Range= (0 - 100)	Description	Very Low	Low	Moderate	High	Very High	Moderate	Moderate	Low
		Value	≤ 0.003	≤ 0.006	≤ 0.009	≤ 0.012	≤ 0.015	≤ 0.009	≤ 0.009	≤ 0.006
	Iron Concentration (Action Level at 10 % + ve Sample for 0.3 mg/l Range= (0 - 100)	Description	Very Low	Low	Moderate	High	Very High	High	Very High	Low
		Value	≤ 0.1	≤ 0.15	≤ 0.20	≤ 0.25	≤ 0.3	≤ 0.25	≤ 0.3	≤ 0.15
	Total Coliform Bacteria (% positive samples in a month)	Description	None	Rare	Few	Occasional	Often	Rare	Few	None
		Value	0	≤ 1	≤ 2	≤ 4	≤ 5	≤ 1	≤ 2	0

* -- A value of 1.0 is subtracted from the normalized value change the order so that lower normalized value corresponds to lower number of condition rating implying better condition

AHP Based Level of Service Quantification and Assessment

After using AHP service percentiles were given to different measures of performance where each sub-factor decomposed weight (output of AHP) is multiplied by the attribute effect value which resulting in an LOS scores contributed by each performance measure towards the overall Service Percentile of the asset. Then all the LOS scores are summed to calculate the Water Main Service Percentile (WMSP). Existing and targeted service percentiles were determined as shown in Table II.8.

Table II.8: Service Percentile Values of Water Using AHP Model of LOS

Service Percentile	Existing	targeted
Water Asset	0.5249	0.7685

The existing LOS score (.525) reflects the current status provided service of the utility and the targeted score (.769) is the goal set by the utility in regards to level of service which means that there is a gap of (0.244) needed to reach the set target for LOS .

Fuzzy Alpha Cut Theorem Based LOS-Condition Mapping Function

The fuzzy mapping function which is based on an algorithm that was used to map condition rating which was determined by the fuzzy weighted sum model to the desired LOS of the asset and that led Khan (2014) to the condition of water main that corresponds to the performance based LOS. The process involved the application of the fuzzy α-cut algorithm were the weights of the different performance measures for condition rating were represented by fuzzy letter grades. The quantitative assessment of condition improvement needs was determined by calculating the difference between the existing and targeted condition ratings as shown in Table II.9 below.

Table II.9: Condition Rating Values of Water Assets

Asset Type	Existing	Targeted	Required Condition Improvement
Water Asset	0.4316	0.2416	0.19

Limitations

1. Performance measures that were used to reflect LOS were the same ones used with condition rating and that didn't reflect the true character of LOS approach which is different than the condition of assets.

2. The performance measures that were adopted in the aforementioned methodology were based on the best practices recommended by InfraGuide Canada and other published literature. That is why each agency should develop their own performance measures depending on their network size, needs, and targets.

3. Regular asset inspection is requires despite not being an established practice in some utilities.

4. Pipes' accessories should have been considered in the estimation of condition improvement needed and analyzed separately.

II.3.2 WSS Service Quality Model (Prevos 2016)

A conceptual model for WSS LOS was developed by Prevos (2016) to overcome the issue of focusing on intrinsic quality of water supply only which is measured from the perspective of the service provider neglecting the customer's perspective. That conceptual model was derived from a synthesis of literature on service quality in other domains. He validated the model using a qualitative case-study approach in which the views of organizations representing customers in this industry were sought. Provision of water service has always been a monopoly and that is due to the economics of scale of the industry (DiLorenzo 1996), meaning that the maximum efficiency can be achieved by having a single supplier which means that customers can't change the service provider and that reflects on how utilities manage their customers. Hence, there is no incentive fro utilities to maximize the LOS unless there is a threat of defection and that necessitated the regulation of such markets by adopting so-called 'yardstick competition' in which service providers are being compared to peer organizations in similar markets (Braadbaart 2007; Flynn 1990). Range of methodologies to measure WSS LOS exists in the literature, however, they were only focusing on intrinsic quality and none of them was customer-focused. Babakus (1993) was more customer-focused but it only targeted supplementary, omitting core services' customer prescription.

Reticulated Water Supply Service

Water supply chain forms an integral part of the natural hydrological cycle (Grigg 2012) because after using water by the customers it is returned back to the natural environment. However, water has limited usability when its natural environment since it is not fit for human consumption, that is why service providers add value to the water extracted from the natural environment through purification and pressurization of the natural resource, delivering the final product to the customer's premises. Tap water provision is a service because customers only pay for the value added by the service provider. Water is forced to return back to the environment through evaporation or water flow. Thus, consumption is defined by quality reduction in technical parametrise i.e: purity and pressure (Zetland 2011). There are certain credence qualities of water service that the customer can't evaluate since he does not have the knowledge or skills to do so (e.g. chemical and biological composition of water required to maintain public health) (Rushton and Carson 1985). In reticulated water supply service, the service provider does not interact with the customer as much as most of other services. However, this can be true when core services are described i.e.actual water supplied to the customer's tap. On the other hand, The Supplementary services such as information provision, billing, and complaints handling require more interaction between the customer and the service provider (Grönroos 1990). The aforementioned characteristics of water supply service are essentials in defining a model for service quality (Prevos 2016).

Service Quality Models

Service quality definition importance comes from being a driver to decision making and its relationship to costs, profitability, customer satisfaction and positive word of mouth. There are two schools of thoughts when it comes to service quality models, the Anglo-Saxon and the Nordic model (Brogowicz et al. 1990). One of the most dominating service equality models is the SERVQUAL gap-model approach (Parasuraman et al. 1993) in which service quality was conceptualized as a gap between what the customer expects from a class of service providers and their evaluation of the performance of a particular service provider. The SERVQUAL construct consists of five dimensions, i.e, reliability, assurance, tangibility, empathy, and responsiveness, four of which are related to intangible elements of service provision.

Conceptual Model (Prevos 2016)

Several performance measurement models/methodologies for water services have been reported in the literature on water supply but most of them were heavily weighted towards supplementary services which is very different than core services due to the higher level of interaction between the customer and the service provider, plus the fact that supplementary services are less tangible than core ones. Hence, the inclusion of core services in LOS measurement is essential because most of the interaction between the service provider and the customer happens at the tap. Prevos (2016) made a distinction between core and supplementary services by representing core services by (technical quality) and supplementary services by (functional quality). Technical quality constitutes the set of measurable physical parameters of the tangible aspects of the service, as perceived by the customer, i.e. the level of purity or pressure of the core services. Due to the lack of customer interaction in the provision of core services in water, it is reasonable to propose that functional quality in water supply is fully located in the supplementary services, e.g. billing, information provision and so on.

Different Water quality measurement approach

The United States Environmental Protection Agency (EPA) uses a non-score approach called TMDL to measure the water quality for water bodies by measure the maximum amount of pollutant allowed to enter a water body (EPA 2017). Based on that approach, pollutant reduction target is identified and then load reductions are allocated. The TMDL is calculated using Equation II.7:

$$TMDL = \sum WLA + \sum LA + MOS \tag{II.7}$$

Where WLA is the sum of waste load allocation at point sources such as: waste water treatment facilities, storm water discharges and concentrated animal feeding operations (CAFOs); LA os the sum laod allocations at non-point sources or the remaining sources of pollutants such as natural background sources; MOS is a margin of safety.

Technical Quality: Core Services

Operators of drinking water at any utility are required to comply with local regulations and standards. However, this can lead to a reduction in service quality (e.g.adding chlorine is essential to ensure public health in that it destroys micro-organisms. In some communities, however, chlorine is perceived as an unwanted chemical, leading to a reduction in service quality). That necessitated the distinction between what is so called intrinsic and extrinsic quality. The customer assesses the service based on his own perception, knowledge, and skills, on the other side, the service provider's assessment of the service is perceived as being intrinsically within the service itself. Extrinsic quality is mainly based on customer's perception while intrinsic quality is embedded within the service provided itself and included credence qualities that cannot be observed by the customer. That is why technical quality has to be looked at from two perspectives, intrinsic and extrinsic. Customers pay for service with their money and time and this notion is very important especially in services as production and consumption occur simultaneously. In developed countries, residential water consumption time-price is negligible because of technological advancement in hydraulic and chemical engineering. On the contrary, some areas do not have reticulated water and such technological deficiency causes women to spend hours every day to obtain water. Time-price is also taken into consideration when the core service does not meet the customer's expectations whether for purity or pressure issues, meaning that, customers only pay additional time in cases of service failures, because water might need to be boiled before it is suitable for human consumption due to treatment failures. Using the time-price concept and its relation to service failures, the (likelihood that a moment of truth is confirmed i.e.the likelihood that expectations are met at each interaction with the service provider) will be the measure for intrinsic technical quality. Prevos (2016) used the methodologies developed for Six Sigma improvement system (George 2003) to express the LOS in Defects per million Opportunities (DPMO) using Equation II.8:

$$DPMO = \frac{disconfirmations * 10^6}{2 * MomentsofTruth * Population} \tag{II.8}$$

To demonstrate the preceding equation, the following example is presented; A water utility serves a population of 100,000 people who each use their tap an estimated ten times per day. On average, a service failure occurs to 10 customers in the system where water is dirty or not available for a period of half a day. This can be expressed as 50 disconfirmations of service expectations regarding purity. The level of service for that day expressed in DPMO equals 25. By using the six sigma table, the 25 DPMO corresponds to 99.998%, which means that in 99.998% of all Moments of Truth in the core service, expectations were confirmed. The extrinsic perspective of technical quality can be simply articulate into sensory verification, i.e. visual verification. since it is the only possible method that the customer possess.

Functional Quality: Supplementary Services

Low levels of tangibility and high levels of interaction between the service provider and the customer are among the main characteristics of the functional quality. The model used for supplementary services consisted of 15 elements : (1) Billing accuracy, (2) Reliability of services, (3) Efficiency of services, (4) Customer service, (5) Safety consciousness, (6) Dependability, (7) Knowledge level of employees, (8) Providing services at the promised time, (9) Responsiveness, (10) Reassurance and understanding, (11) Having customers' interest at heart, (12) Willingness of employees to assist customers, (13) Quality of management, (14) Billing clarity, and (15) Politeness of employees.

Level of service can thus be defined as the amount and kind of service that, on one hand, is appropriate to the needs and desires of the customers and, on the other, is not high enough to be impossible to attained given the available resources.

II.4 Artificial Neural Network (ANN)

Most of the data that exists in the real world have certain levels of noise and these data should be used for prediction purposes. This is where artificial neural networks (ANN) have played an important rule in that area. Basically, ANN mimic the ability of the human brain in predicting patterns based on learning and recalling processes. ANN has a prediction ability since it learns automatically by example. ANN best use is when the relationships among variables are unknown. ANNs consist of a large number of neurons which are connected in different layers (input, hidden, and output). A report conducted by ASCE (2000) showed that ANN is a good methodology for pipe condition assessment without excavation. Hence, it has been utilized in that domain in many areas in the literature to predict the condition of the pipes.

II.4.1 Back-propagation Neural Network (BPNN) Technique

An algorithm that was first proposed by Paul Webos in 1974, after that it was re-discovered by Rumelhart and McClelland in 1986 to address the learning problem for multilayer networks. BPNN learn by example and can be used to make predictions. Artificial neurons receive information from other neurons, process it, and then send the filtered information to the other neurons (Tsoukalas and Uhrig 1996). BPNN comprises three layers which are: an input layer (n), at least one hidden layer (h), and an output layer (m), as shown in Figure II.7. units are connected in a feed-forward fashion where inputs are connected to the hidden layer, and hidden layer is connected to the output layer. Each neuron receives weighted inputs from other neurons and communicates its output to other neurons by using an activation function. The following is a description of each layer as shown in Figure II.7 (Chou and Pellinen 2005; Tsoukalas and Uhrig 1996): **Input Layer**: input neurons which receive information and the value of the input information, **Hidden Layer**: neurons here process the incoming information based on the stored experience through training. That is achieved by receiving the weighted values of the input neurons and computes the value to send to the output neurons. The values of the hidden neurons and the weights of the connections form the internal representation of the network are completely computed by the network, that is done without human interference. The hidden layer contains unknown knowledge (Black box) of the relations that lie between different patterns, and **Output Layer**: neurons here receive the weighted output of the hidden neurons and then compute the output filtered pattern.

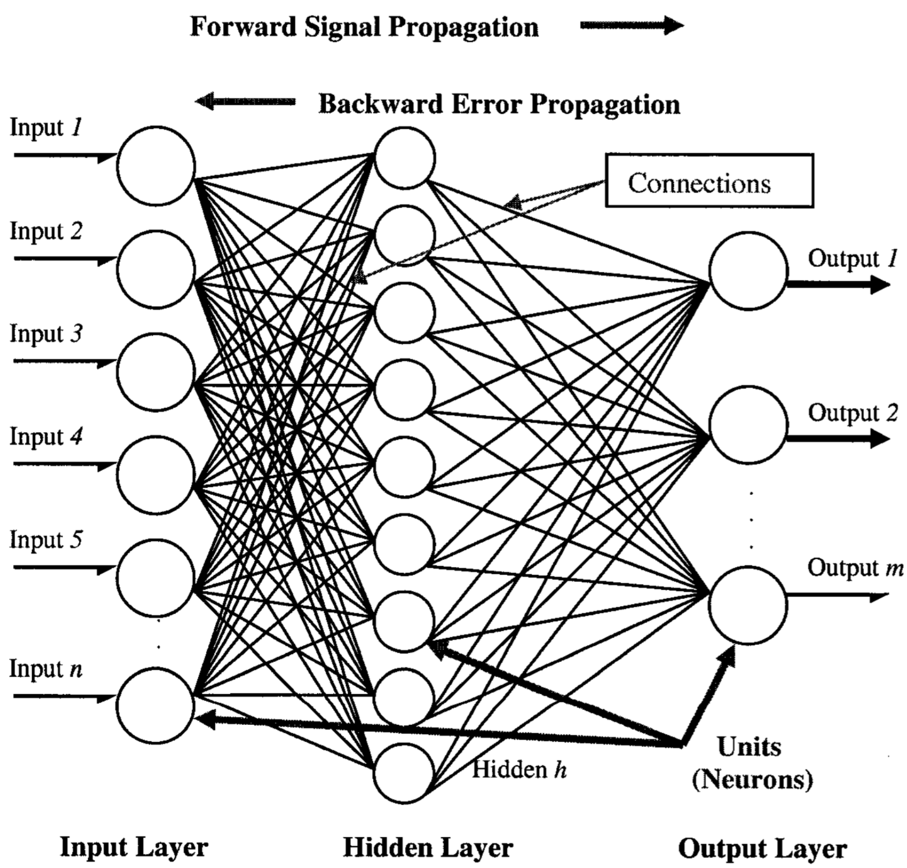

Figure II.7: Schematic Architecture of the (BPNN) with One Hidden Layer

II.4.2 (BPNN) Learning and Recalling Processes

The Back-propagating is a supervised learning algorithm where the output is provided to the ANN so to train itself (Tsoukalas and Uhrig 1996). Here, the network training happens with a known data set of input-output pairs in which the input is presented to the network and then the output is estimated.After that, the estimated output is compared with the actual one resulting in an error value. That error is backwardly propagated through the network to enhance prediction accuracy by adjusting the values of connection weights. Hence, the more cycles are completed the closer the output is to the actual pattern until actual and estimated outputs are totally or almost equal, or a previously-specified allowable error limit is reached. After the training process is completed, the network can be used to solve problems by feeding the network with new inputs similar to the ones used trough training process and an output pattern is obtained based on the computed ANN weight structure that was already trained during the learning stage. A learning rate value is specified by the model designer. The learning rate, a common parameter in many of the learning algorithms, and it affects the speed at which ANN arrives at the minimum solution. It applied a greater or lesser portion of the respective adjustment to the old weight. Hence, if the factor is set to a large value then the neural network may learn more quickly, but if there is a large variability in the input set then the network mat not learn very well or at all. For example, if the learning rate was set to be (0.01), then it will take 100 patterns to make 1% adjustment. Lower learning rate requires more iterations and vice versa.

II.4.3 (BPNN) Validation Process

Validation of ANN developed model is done by testing how well the neural net developed predicts untrained patterns by using an unknown data set. Validation can be executed by using common error metrics such as the mean absolute error (MAE), root mean square error (RMSE), or mean absolute percentage error (MAPE) (Dikmen et al. 2005).

II.5 Limitations of Previous Work

To sum up, the industry is shifting toward a more value-driven management systems and the top priorities for any utility are swapping around: customer satisfaction, ROI, Budget allocation. Hence, a utility that does not take the customer into consideration won't be as efficient as the one that does.

After reviewing the technical literature the following limitations were found:

- Adopted measures of different performance assessment models do not reflect the unique nature of LOS which is very different than condition level. The use of quality of service metrics adopted in a performance assessment model such as the International Water Association (IWA) addresses this gap.

- Subjectivity in LOS developed models is an obstacle for utility engineers which hinders them from adopting these models. The use of the Best-worst Method (BWM) to convert experts feedback to relative weights for each LOS factor solves this issue.

- Most of the technical literature either deals with LOS or condition separately with no emphasis on the relationship between both approaches. The use of Artificial Neural Networks (ANN) to map LOS to Condition closes the gap between condition assessment and level of service.

Chapter III

RESEARCH METHODOLOGY

The proposed research methodology, as shown in Figure III.1, is comprised of the following steps:

- Literature review: A thorough review of the recent research work in the area of customer-driven infrastructure asset management and water networks performance assessment is given;
- Level of Service (LOS) and condition factors identification: The defining factors are used in the model to determine the Level of Service supplied by any water utility;
- Level of Service (LOS) model development using Best-Worst Method (BWM): Best-Worst Method (BWM) is used to calculate the aforementioned factors' relative weights of importance using an experts questionnaire answers;
- Data collection: The WDN condition and LOS factors data – i.e. the Montreal water networks data of the age and breakage of pipes – is collected. Besides, the Level of Service data is collected using the CAREW-W report, created by the National Engineering Laboratory (LNEC) on a Research Technology Development (RTD);
- The Artificial Neural Network for mapping LOS to the condition: The mapping de-fines to what extent the Level of Service is affected by a network's condition changes;
- Conclusion and recommendation: A thorough look at the model case study results.

In order to develop the mapping model, a literature review is performed of municipal infrastructure performance assessment models and approaches and latest level of service oriented ap-

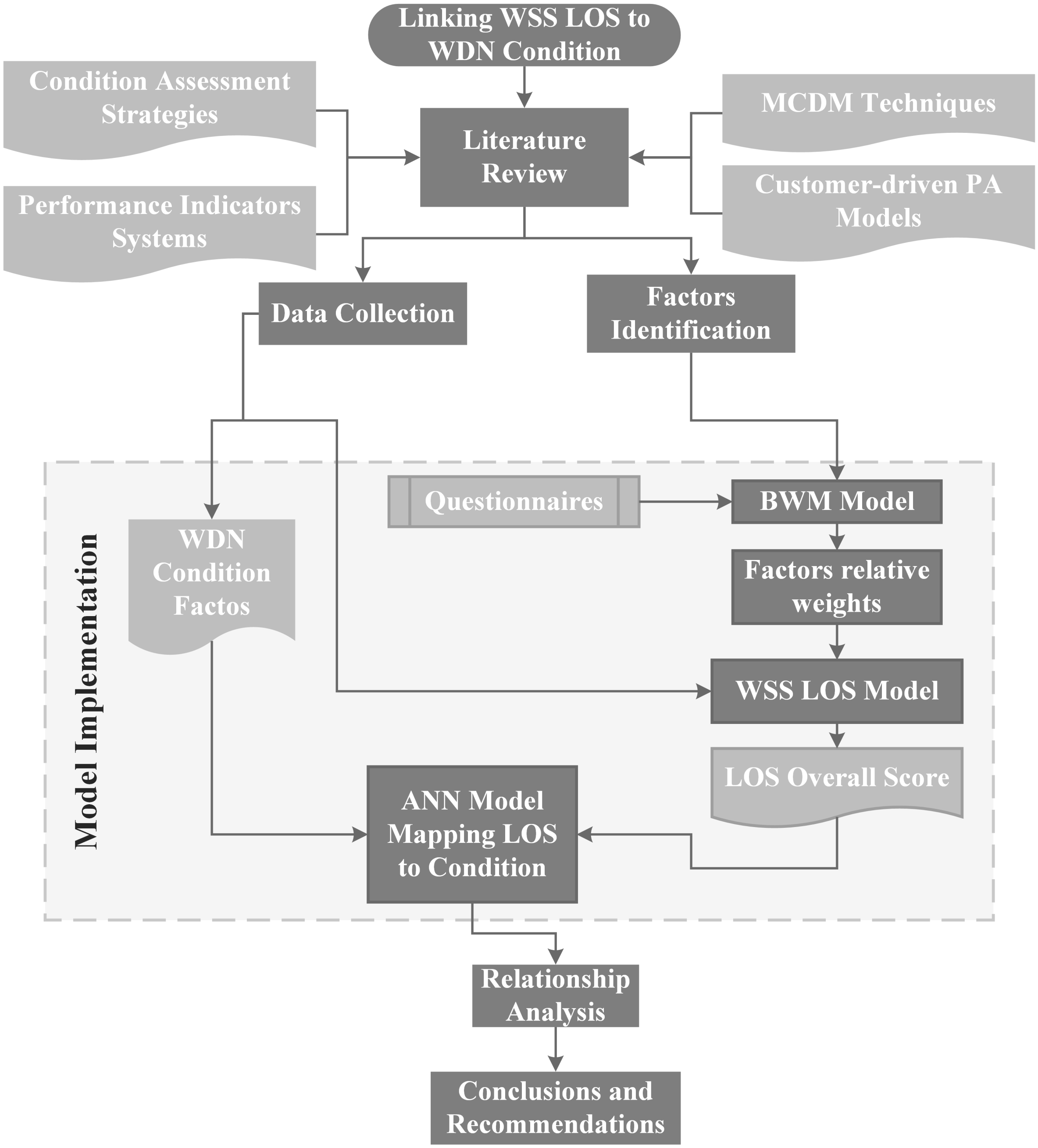

Figure III.1: Research Methodology Flowchart proaches. Performance indicators of different systems are reviewed and most suitable factors were chosen for the definition of both the level of service of the water systems and condition of the pipes to be used in the model development. After factors identification, a multi-criteria decision making technique which is the Best-Worst Method (BWM) is used to extract the relative importance of the previously chosen factors from questionnaire results. Data of both level of service and condition factors are collected to act as inputs to the later developed model. Artificial neural networks were used to map condition factors to level of service overall scores. The results of the ANN model are analyzed and discussed.

III.1 Literature Review

Discussed thoroughly in Chapter II, a summary of Literature Review is as follows:

Section II.1 reviews different condition assessment strategies, adopted by different water utilities or existing in the technical literature. It discusses the different types of approaches for asset management and clarifies why a service-driven approach should be adopted. Besides, the relationship between business drivers and utility capabilities and how assets are managed for any utility are defined. Then, the performance indicator systems adopted by different organizations worldwide are shown, and compared to define the advantages and disadvantages of those systems. Section II.2 discusses MCDM, its applications in different domains and the most popular techniques and methodologies that have been implemented. An overview of the Analytic Hierarchy Process (AHP) techniques is given, followed by a new methodology called the Best-Worst Method (BWM). A comparison between the two techniques reveals that BWM performs better than AHP. Section II.3 discusses the Level-of-Service (LOS) developed models in the technical literature with an emphasis on Khan (2014) and Prevos (2016) models. Their methodologies and limitations are also discussed.

III.2 Level of Service (LOS) Model

III.2.1 Factors Identification

In order to define the Level of Service, the model should be built on a system of measures. These measures should reflect the unique nature of the Level of Service and include both its intrinsic and extrinsic qualities. They target only the core services, i.e. the technical qualities, of the water utility and the supplementary services are not the focus of this research. Table III.1 shows chosen LOS factors with their description and corresponding variables which form these factors. The International Water Association (IWA) system was used for (Customer Complaints) and (Pressure and Continuity) factors. The approach used for (Water Quality) was the same adopted by Colbian Water, a regional water corporation in Victoria. It provides an overall view of the system performance by using a catchment-to-consumer approach which facilitates the communication of the relationship of water quality from the catchment to consumers; The following three main factors define the water quality: (1) barrier effectiveness: a proxy for treatment plant performance which reflects the extent of control over the process not the water quality leaving the plant, (2) network protection: comprises several sub-factors which are part of Coliban Water's laboratory testing monitoring system, (3) regulations: added to prevent eclipsing. Eclipsing happens when insufficient points are assigned to a very important or significant event; The network protecting factor does not incorporate all the factors that might cause health risks and thus suspicions of water contamination or non-complying drinking water incidents are incorporated in this factor.

III.2.2 Best-Worst Method (BWM) for LOS Factors

To calculate the relative importance of LOS main factors with respect to the overall LOS score and the relative importance of each sub-factor, i.e. type of customer complaints, to the main factor, i.e. customer complaints, the Best-Worst Method is chosen. The implementation goes through the following steps:

Table III.1: LOS Chosen Indicators

Water Quality		
Barrier Effectiveness	Network Protection	Regulations
Pressure and Continuity of Supply		
Interruptions per connection		
(Number of interruptions/number of service connections x 1000)		
Customer Complaints		
Water Quality Complaints	Interruption Complaints	Pressure Complaints
(Number of water quality complaints during the year/number of service complaints during the year x 100)	(Number of complaints due to supply interruptions during the year /number of service complaints during the year x 100)	(Number of pressure complaints during the year / number of service complaints during the year x 100)

1. Respondents choose the best and worst factors, followed by pair-wise comparisons indicating the preference of the best criterion over all the other criteria using a number between 1 (equally important) and 9 (extremely more important). For example, R1 column corresponds to the first respondent's answers which comprises: (1) a_{BW} = 8, which means that the chosen best factor is 8 points more important than the chosen worst factor, (2) a_{b1} = 6, which means that the chosen best factor is 6 points more important than the factor number 1.

2. Respondents are asked to indicate the preference of the other criteria over the worst criterion,

using a number between 1 and 9. For example, a_{w1} = 6, which means that factor number 1 is 6 points more important than the chosen worst factor.

3. Data from the questionnaire results are acquired, the respondents' input sheet is created, with the following information for each respondent:

   - Comparison value (1-9) of the best factor against the worst one (e.g.Abw),
   - Comparison value (1-9) of the best factor against the other factors (e.g.Ab1, Ab2,etc.),
   - Comparison value (1-9) of the other factors against the worst factor (e.g.A1w, A2w,etc.) as illustrated in Table III.2.

Table III.2: Example of The Respondents Input Sheet

Respondants	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12
Abw	8	9	9	9	9	7	8	8	9	9	9	9
Ab1	6	7	5	7	6	5	6	6	8	7	6	9
Aw1	6	9	9	6	6	5	6	6	8	8	6	7

4. Optimal weights are calculated for the criteria (i.e. w_1^*, w_2^*, w_3^*,...w_n^*), where for each pair of w_B and w_j, we have $w_B/w_j = a_Bj$ and $w_j/w_W = a_jW$. This can be satisfied by minimizing the maximum absolute difference for $\left| \frac{w_B}{w_j} - a_{Bj} \right|$ and $\left| \frac{w_j}{w_W} - a_{jW} \right|$ which results in the problem shown in Equation III.1:

$$\begin{aligned} min\ max\{ \left| \frac{w_B}{w_j} - a_{Bj} \right| , \left| \frac{w_j}{w_W} - a_{jW} \right| \} \\ s.t. \\ \sum_j w_j = 1 \\ w_j \geq 0, for\ all\ j \end{aligned} \tag{III.1}$$

Rather than programming tools like MATLAB®, an optimization tool EVOLVER® is used as an EXCEL® plug-in to solve the $minmax$ problem. In order to solve this problem it is transferred to the following mathematical programming problem as in Equation III.2:

$$\begin{aligned} min\ \xi \\ s.t. \\ \left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \xi, for\ all\ j \\ \left| \frac{w_j}{w_W} - a_{jW} \right| \leq \xi, for\ all\ j \\ \sum_j w_j = 1 \\ w_j \geq 0, for\ all\ j \end{aligned} \tag{III.2}$$

The goal of this mathematical problem is to minimize the value of ξ while satisfying three conditions which are: $\left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \xi$, $\left| \frac{w_j}{w_W} - a_{jW} \right| \leq \xi$ and that the summation of all weights $\sum_j w_j$ equals one. After solving the mathematical programming problem, the exact value of ξ^* is obtained. A BWM modeling sheet is created to gather all the responses and calculate the results of the following differences: $\left| \frac{w_B}{w_j} - a_{Bj} \right|$ and $\left| \frac{w_j}{w_W} - a_{jW} \right|$ for each criterion and then minimize the maximum absolute difference. Figure III.2 demonstrates this procedure which starts with the first two steps: filling in the first two tables where the respondent choices of best and worst criteria are inserted. Steps (3 and 4) involve the respondents estimating of how much the best factor is more important than the rest of factors and how much each factor is more important than the worst one. Here in this example, as demonstrated in step 2, the respondent chose (Quality of Supplied Water) as the best criterion, and (Customer Complaints) as the worst one. Then in step 3, he starts to compare all criteria to the chosen best criterion as follows: (1) a_{bb} is the comparison of the best criterion against itself which equals one, (2) a_{b1} is the comparison of the best criterion against (Pressure and Continuity of Supply) which is given 6 points, (3) a_{bw} is the comparison of the best criterion against the chosen worst one which is (Customer Complaints), and it was given 8 points. Moving to step 4 where comparisons of all criteria against the worst criterion is made as follows: (1) a_{bw} is the comparison of the best to the worst criteria which always takes the maximum values of comparison which equals to 8, (2) a_{w1} is the comparison of the (Pressure and Continuity of Supply) factor to the chosen worst factor which equals to 6. (3) a_{ww} is the comparison of the chosen worst criteria against itself which equals one.

Step 1: Decision Criteria Determination

Decision criteria name	Decision criteria abbreviation
Quality of Supplied Water	A
Pressure and Continuity of Supply	B
Customer complaints	C

Step 2: Best and worst criterion determination

Decision criteria classification	Decision criteria classification
Best criterion	A
Worst criterion	C

Step 3: Preference of the best criterion over the other criteria determination

Best criterion/Other Criteria	A	B	C
Best criterion	R1 - Abb	R1 - Ab1	R1 - Abw
A	1.00	6.00	8.00

Step 4: Preference of the worst criterion over the other criteria determination

Other criteria/ worst criterion	Worst Criterion	C
A	R1 - Abw	8.00
B	R1 - Aw1	6.00
C	R1 - Aww	1.00

Figure III.2: BWM Modeling Sheet Step (1 - 4)

In step (5), initial values of factors relative weights are inserted as shown in Figure III.3 which has a total sum of 1.00 then these weights are used for each factor to calculate:

$W_B/W_j - a_{aj}$ and $W_j/W_W - a_{Wj}$ for which the maximum value is added to the (Max. j) column, at last, the maximum value of these maximums are added to the objective cell. This objective value is the value to be optimized, in step (6), using genetic algorithm then weights - of step (5)- will change accordingly during optimization process to reach optimized relative weights.

Step 5: Weights optimization

Decision criteria abbreviation	Weight abbreviation	Decision criteria weight	
A	R1 - w1	0.60	
B	R1 - w2	0.30	
C	R1 - w3	0.10	
Total		1.00	Variables Constraint Met

Step 6: Objective formulation

Decision criteria abbreviation	W_B/W_j - a_{Bj}	W_j/W_W-a_{jW}	Max. j
A	0.00	2.00	2.00
B	4.00	3.00	4.00
C	2.00	0.00	2.00
Objective			4.00

Figure III.3: BWM Modeling Sheet Step (5) and (6)

Then an optimization summary sheet is created, including the optimization process that leads to obtaining the optimized weights. In Figure III.4, constraints are set to be zero when the sum of the main factors equals 1. Consistency index ($\xi \max$) is calculated using the abw (best-to-worst comparison value) and the information presented in Table II.4. The value to be optimized, i.e. objective is (ξ *) restricted by the aforementioned constraints for each respondent. The consistency ratio is calculated by dividing (ξ^*) by ($\xi \max$). This value reflects whether the respondent's answers are consistent or not (Rezaei 2015). This aspect of BWM is relative to the model user. Any value that surpasses (1) is considered inconsistent.

Weights Calculation (optimization)

AVG Weight		Variables	R1	R2	R3	R4	R5
0.51	Quality of Supplied Water	w1	0.60	0.50	0.50	0.70	0.60
0.34	Pressure and Continuity of Supply	w2	0.30	0.10	0.40	0.20	0.30
0.15	Customer complaints	w3	0.10	0.40	0.10	0.10	0.10
1.00							

	R1	R2	R3	R4	R5
Constraint	0	0	0	0	0
abw	8.00	9.00	9.00	9.00	9.00
Consistency Index (ξmax)	4.47	5.23	5.23	5.23	5.23
Consistency Ratio	0.89485	1.09943	0.95602	0.76482	0.76482

	R1	R2	R3	R4	R5
Objective ξ*	4.00	5.75	5.00	4.00	4.00

OBJECTIVE	31.75

Figure III.4: Example of BWM Optimization Summary Sheet

III.2.3 Water Quality Factors

In order to identify what water quality means from a customer perspective, Coliban Water - a regional water corporation in Victoria, Australia - approach was adopted. According to Prevos (2015), any water sample has many features and, to form a water quality index, it is essential to choose the most important factors. He adopts a catchment-to-consumer approach with the following factors:

- Catchment protection

- Barrier effectiveness
- Network protection
- Regulatory compliance
- Customer perception .

In this study, catchment protection is excluded from the proposed model because Coliban Water has no available methodology for measuring that performance. Customer perception was also excluded as the customer complaint factors are added to the LOS model, reflecting the customer perception of drinking water quality well enough. A mixture of numerical measurements (SCADA and laboratory data) and events (regulatory notifications) calculate these factors. To determine the relative importance of each factor, 36 water quality experts from Australia, New Zealand, Europe and the US rate these factors on a scale of 1 to 100 to indicate the importance of each factor. Figure III.5 shows the responses.

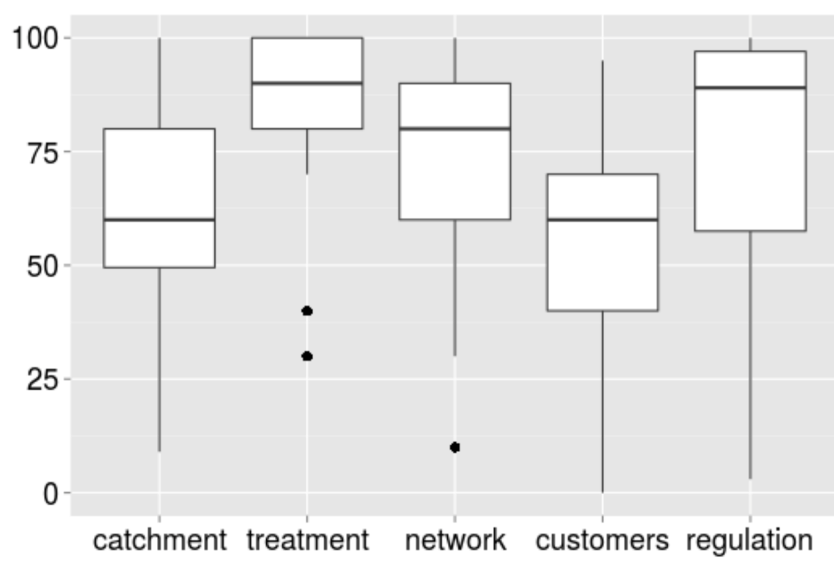

Figure III.5: Perceived Importance of Factors

Box and Whisker plots are used to represent the data collected through quartiles. The vertical lines extending from the boxes represent the variability out of the upper and lower quartiles, these lines are called whiskers. Outliers are represented by the individual black dots which are out of the whiskers range. The plot doesn't make any underlying assumptions of the data distribution. The spacing between the box different parts reflect the skewness and spread of data, the box itself represents the Inter Quartile Range (IQR). The median is represented by a horizontal line which lies in the box area which will be used later to assign optimal scores to each factor because the median is considered a more robust measure than the mean. Barrier effectiveness had the highest number of points (90) and that might be due to the impact that any inefficiency in the treatment process might have on water quality and how much it contributes to the whole water provision process. Regulations came second with (89) points since this factor accounts for health risks which have a great importance. Network protection came third with (80) points and in the last place was customer perception with (60) points because of the customer's limited technical knowledge about water quality. In Table III.3, median scores are used to assign the optimal scores to each water quality factor.

Table III.3: Water Quality Index Factors

Factor	Median Score	Optimum factor score	
		Calculated	Rounded
Catchment	60	-	-
Barriers	90	282	300
Network	80	251	250
Customers	60	188	200
Regulation	89	279	250
TOTAL	348	1000	1000

The catchment factor was excluded by Prevos (2015) since there was no methodology available to measure the performance of catchment. The maximum score was set to be 1000 by normalizing each factor to allow for a sufficiently large number of points to be assigned to each factor. This method depends on a psychological principle called distance effect: The closer the distance between two numbers, the harder is it to discriminate between them. In other words, if the sub-factors scores are too close to each other, they will not be seen as different in terms of importance (Moyer and Landauer 1967). Optimum scores were rounded to the nearest 50 to ensure sufficient numerical distance between factors and that was the reason that the (reulatio) factor was rounded downward to ensure that the total added to 1000 (Prevos 2015). The optimum A set of formulas is used to convert each factor to a non-dimensional score, to integrate it with the other factors in the LOS model.

1. Barrier effectiveness provides an indication of the performance of the process, not the water quality itself. The factors depend on the number of alerts at critical control points for each of the treatment barriers as demonstrated in Equation III.3:

   $$F_t = 300 - (5alert) - (15critical) \tag{III.3}$$

   Using the preceding equation, critical alerts are multiplied by 15. On the other hand, normal alerts are multiplied by 5. For example, if we have 10 critical alerts and 10 normal one, the F_t score will equal (300 - (5*10) - (15*10) = 100 points for the barrier effectiveness parameter.

2. Network protection consists of several parameters which are chosen by Coliban Water; Based on the experts' opinion survey, each parameter is assigned a weight as in Figure III.6. E-coli came in the first place as the most important sub-factor of network protection fator

with a mean of 98 points, followed by Chlorine and Turbidity with 90 and 78 points, respectively, at last came Colour and pH sub-factors with 50 points each. Similar to Table III.3, weights are normalized in order to have a sum of 250 points, then they were all rounded as in Table III.4 which shows the resulted points for each sub-factor of Network Protection.

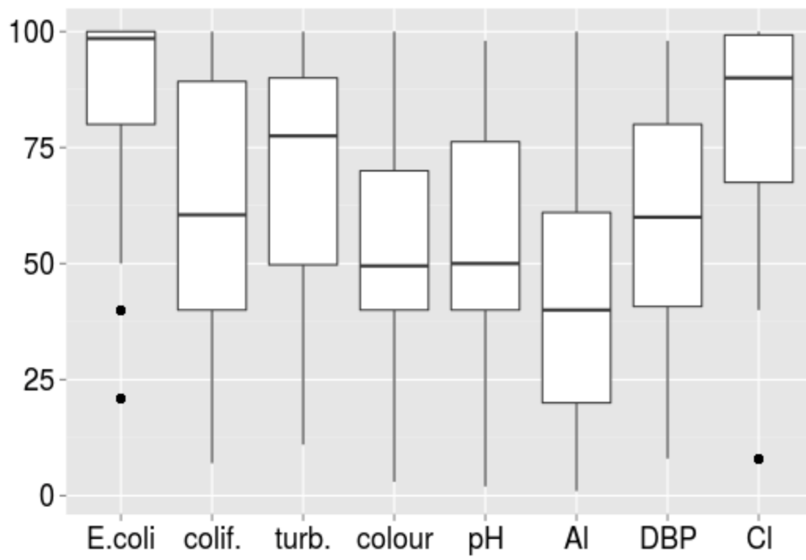

Figure III.6: Perceived Importance of Network Protection Sub-factors

Table III.4: Network Protection Sub-factors

Factor	Median Score	Optimum factor score	
		Calculated	Rounded
E.coli	98	47	45
Coliform	60	29	30
Turbidity	78	37	35
Colour	50	24	25
pH	50	24	25
Aluminium	40	19	20
DBP	60	29	30
Chlorine	90	43	40
TOTAL	348	250	250

3. Regulatory compliance is added because the network protection factor can't cover all the aspects that can cause a risk to the public health. Equation III.4 explains this parameter,

according to Prevos (2015) this factor is either 250 or 0. Depending on whether a notification has been lodged to the department of health or not, notifications depend on each city's health regulations and standards. For example, if a water system has a perfect score on all aspect of water quality expert that leads the system to exceed the safety levels, the index will be deducted 250 points resulting in 75% of the maximum value.

$$F_c = 250 - (notifications = 0) \tag{III.4}$$

Finally, the total score is calculated by summing the three main factors and then dividing them by 100 so that the maximum value is 10; then water quality can be included in the LOS model. The main factors' weight sum will total 800 since the customer perception was excluded; thus, the weights' points are normalized for a total of 1000, resulting in the following weights:

- Barrier effectiveness = 350,
- Network protection =310,
- Regulation =340.

Here, the Water Quality and Pressure & Continuity of Supply factors are considered intrinsic factors of the service and the Customer Complaints is considered an extrinsic factor because it requires a higher level of integration between the service provider and the customer. Besides, the level of tangibility for Customer Complaints is lower than in intrinsic qualities with a higher level of tangibility, like water quality and continuity of supply. Factors chosen to represent the Water Distribution Network are breakage rate and the pipe age for Water Distribution Network (WDN) in a certain zone.

III.2.4 LOS score calculation

A fuzzy expert system is used for both the pressure & continuity of supply and the customer complaints, to derive the effect value which will be multiplied by the calculated weights from the previous steps. A fuzzy expert system is an expert system that uses a collection of fuzzy membership functions and rules, rather than the Boolean logic, to reason about data. Membership functions are chosen based on expert opinions and following simple logic based on the quantitative ranges of the indicated factors from the experts' feedback. Therefrom most of the functions were chosen to be within the linear category either triangular or trapezoidal. For example, if x and y are input variables with known values and z is the output variable to be computed, the rules will be similar to the following: If x is low and y is high, then z = medium. Matlab® fuzzy toolbox is used to create the system in order to find a non-dimensional value compatible with the developed LOS model's other factors.

Pressure and Continuity of Supply

Interruptions per 1000 connection is the variable used for pressure and continuity of supply. Based on a study by Alegre et al. (2004), the mean value of the collected results is 12 interruptions per 1000 service connection. Triangular membership functions are used to create the fuzzy expert system input variables, as shown in Figure III.7. These functions can be changed based on experts perspectives for each utility. Here, the mean value extracted from Alegre et al. (2004)'s case study was used in the center of the middle membership function and the rest of the functions are assumed based on the minimum and the maximum values of the case study. The first membership function (MF1) was assumed to range from 0 to 12 and the third one (MF3) to range from 20 to 50 which is the maximum value obtained from the case study. The output of this fuzzy expert system as shown in Figure III.8, is evenly distributed over three triangular membership functions: Low, medium and high. The output of this step was a value ranging from (0-1) which was then multiplied by 10.

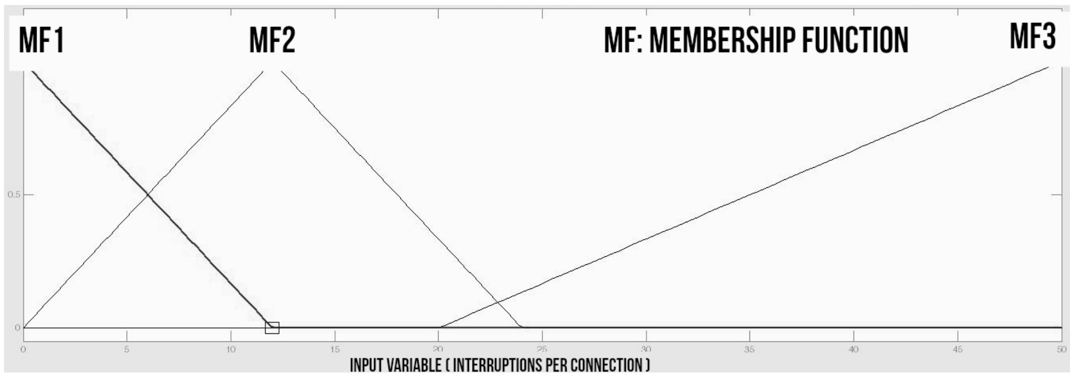

Figure III.7: Fuzzy Expert System Input Membership Function Plots for Interruptions

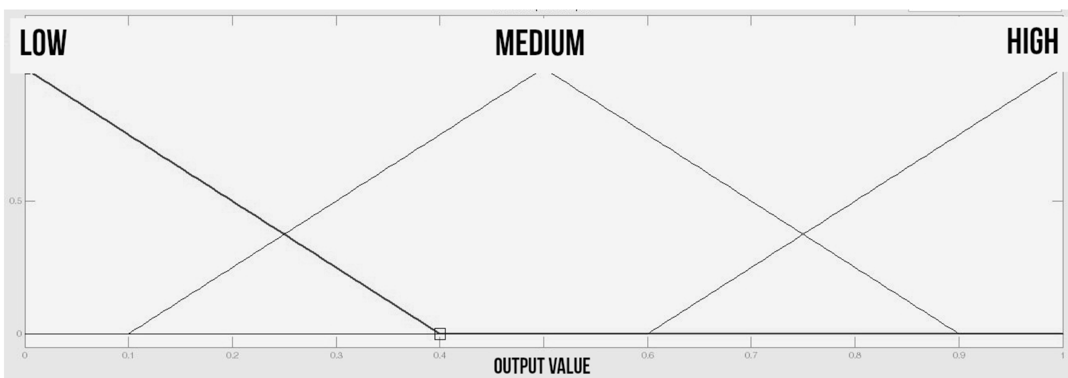

Figure III.8: Fuzzy Expert System Output Variables for Interruptions

Customer Complaints

The same procedure for Pressure & Continuity of Supply is used for customer complaints sub-factors where the mean values of Alegre et al. (2004)'s case study for each factor was used as the center of the middle function and the other two membership functions were assumed based on the maximum value - which is 100% - and the minimum value - which is 0% - for all customer complaints sub-factors, i.e. water quality complaints, interruption complaints and pressure complaints as shown in Figures III.9 III.10 and III.11. The variable that was used for any type of customer complaints is defined as the number of this specific type of complaints during the year/number of total service complaints during the year x 100. The mean value of the study results by Alegre et al. (2004) for the pressure complaints is 46%, the first membership function (MF1) was assumed to range from 0 to 40% and The third one (MF3) was assumed to range from 60% to 100%. The mean value of the collected results for the interruption complaints is 16%, the first membership function (MF1) was assumed to range from 0 to 16% and The third one (MF3) was assumed to range from 27% to 100%. The mean value of the collected results for the water quality complaints is 18%, the first membership function (MF1) was assumed to range from 0 to 18% and The third one (MF3) was assumed to range from 30% to 100%. For the output membership functions which are shown in Figure III.8, the three membership functions where distributed by the system's defualt settings as follows: (1) First membership function ranges from 0 to 0.4, (2) Second membership function ranges from 0.1 to 0.9 with a middle point of 0.5, (3) Third membership function ranges from 0.6 to 1. This output results in a value between 0 and 1, which is also multiplied by 10.

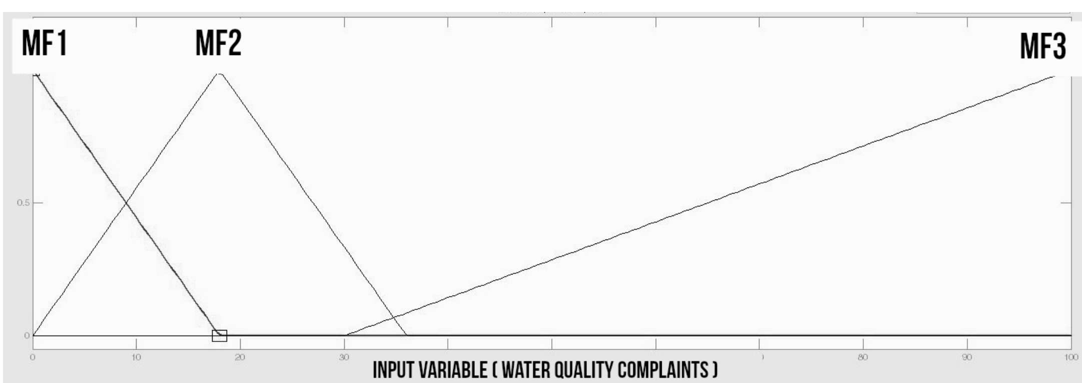

Figure III.9: Fuzzy Expert System Membership Function Plots for Water Quality Complaints

Water Quality

To transform the aforementioned parameters that constitute the water quality factor to a non-

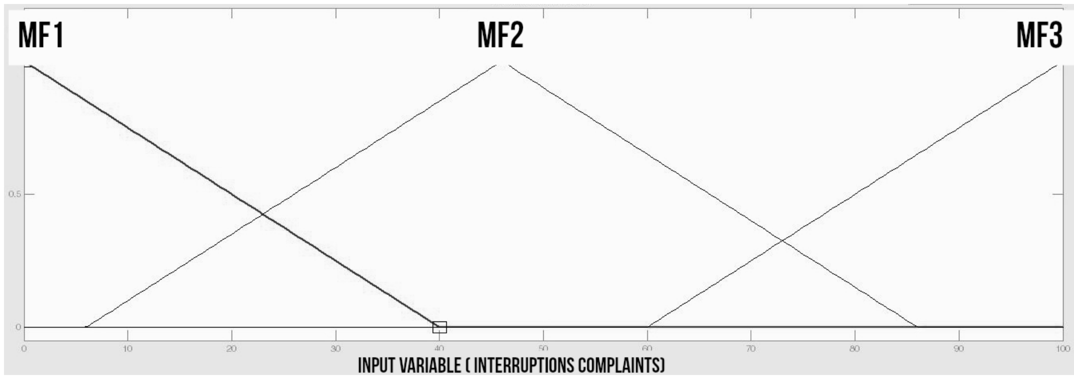

Figure III.10: Fuzzy Expert System Membership Function Plots for Interruption Complaints

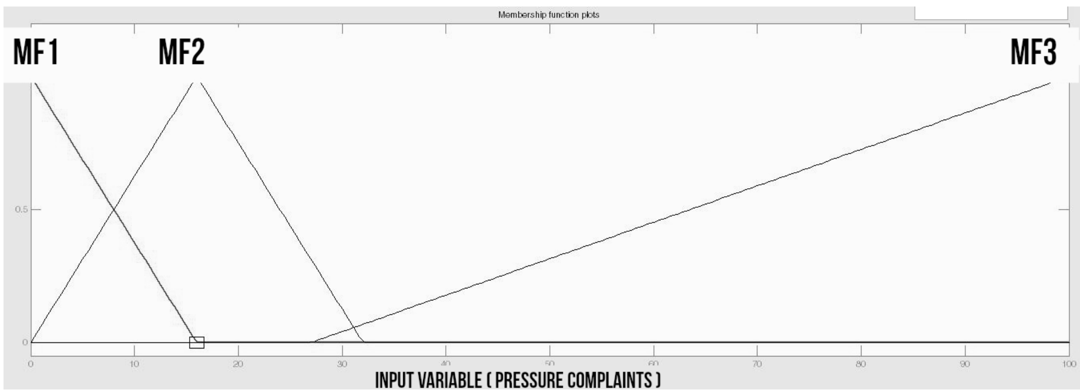

Figure III.11: Fuzzy Expert System Membership Function Plots for Pressure Complaints

dimensional scores, NHMRC (2011) guidelines are used to derive all the following formulas.

- E.coli is assigned 45 points if there is a total absence of it in all samples, Equation III.5:

$$f_1 = 45(ecoli = 0) \tag{III.5}$$

- Coliform doesn not account for health-related parameter according to NHMRC (2011); However, it is existence indicates that there might be a contamination that has occurred post-chlorination. Thus, 30 points are assigned if there is a 90% absence in all samples according to Montreal regulation requirements as in Equation III.6:

$$f_2 = 30(coliform = 0) \tag{III.6}$$

- Turbidity is calculated using a segmented linear function with a given zero score if NTU is greater than 5, 1 NTU is the target value for effective disinfection according to NHMRC (2011), and 0.2 NTU is the ADWG target for effective filtration of Cryptosporidium and Giardia as in Equation III.7:

$$f_3 = 10(NTU \leq 5) + 10(NTU \leq 1) + 15(NTU < 0.2) \tag{III.7}$$

- The color sub-factor is also calculated using a segmented linear function with two critical values of 5 and 15 HU in order to ensure that the production of disinfection by-products is minimized as shown in Equation III.8:

$$f_4 = 10(colour \leq 15) + 15(colour \leq 5) \tag{III.8}$$

- The pH factor critical value is chosen to ensure an optimal disinfection where full points are awarded when the measurements are within the pre-defined limits. Thus, chlorinated or UV disinfected systems this is between pH 6.5 and 8.5, for the chlorinated systems the ideal range is between pH 7.5 and 9.5 which is reflected in Equation III.9:

$$
\begin{aligned}
f_5a &= 25(pH \geq 6.5 \cap pH \leq 8.5) \\
f_5b &= 25(pH \geq 7.5 \cap pH \leq 9.5)
\end{aligned}
\tag{III.9}
$$

- Acid soluble aluminium critical value is 0.2 mg/L according to NHMRC (2011) which means that full points are awarded when the maximum measured value is less than the critical value as in Equation III.10:

$$f_6 = 20(Al \leq 0.2) \tag{III.10}$$

- The DBP, i.e. disinfection by-products, factor indicates the concentration of total trihalomethanes in the system where the maximum measurement's critical value is 0.25 mg/L as shown in Equation III.11:

$$f_7 = 20(THM \leq 0.25) \tag{III.11}$$

- The chlorine factor assigns points based on the levels of free and total chlorine within the network which should fall within the pre-defined limits where n is the total number of chlorine test results as in equation III.12 :

$$f_8 = \frac{(Cl \geq 0.1) \cap (Cl \leq 4)}{n} \tag{III.12}$$

Here, all tests that resulted in a concentration between (0.1 and 4) mg/L are divided by the total number of tests conducted and then multiplied by 40. For example, if 100 tests were conducted, among them, 80 tests that had results within the aforementioned range, F_8 = 40 * (80/100) = 32 points.

The network protection factors can be calculated using Equation III.13 by simply summing up all the points of its sub-factors:

$$NP = f_1 + f_2 + f_3 + f_4 + f_5 + f_6 + f_7 + f_8 \tag{III.13}$$

Then, the weights for each factor are multiplied by a scaled value or a formula output, depending on the targeted factor. This is extensively demonstrated in the Model Implementation Chapter. The output of this stage is an overall score of the Level of Service for different zones, boroughs or neighborhoods, reflecting the quality of the service provided by the utility. The frequency of gathering data of LOS metrics depend on each metric sampling process but generally the LOS score calculation has to be done at the end of each year to investigate the impact of the current asset management strategy on the service quality in a certain geography.

III.3 Artificial Neural Network (ANN) for Mapping WSS LOS to WDN Condition

Artificial Neural Network (ANN) is a nonlinear model that is easy to use and understand compared to statistical methods. ANN with Back propagation (BP) learning algorithm is widely used in solving various classification and forecasting problems. Even though BP convergence is slow but it is guaranteed. However, ANN is black box learning approach, can not interpret relationship between input and output and cannot deal with uncertainties. The ANN procedure is demonstrated in Figure

III.12. To study the relationship between Water Supply System (WSS) Level of Service (LOS) and Water Distribution Network's (WDN) condition, a Neural Net is trained for future applications, e.g. predicting LOS from WDN data, budget allocation and pinpointing factors that cause LOS degradation. First, input data set is entered into the model, comprised of two main factors: **The pipe age average** and **the pipe breakage average** for a specific zone or neighborhood. Then, the number of hidden layer and neurons in each layer is defined, and the learning rate and momentum are chosen. Output data set is comprised of the **LOS overall score** as the only factor. The process of validation is embedded in the used software which means that the model is automatically recalled and run using the existing data used for training then compared against actual outputs resulting in a specific value of R^2 which reflects the validity of the model. ANN was implemented using the Visual Gene Developer software. The software interface, as shown in Figure III.13 helps the user choose the number of input variables, output variables, hidden layers and the number of neurons in each layer. Here, the input variables are the pipe *age and breakage averages* for each zone and the output variable is the *LOS scores*. The LOS scores from the last step, i.e. BWM model, are added to the model along with age and breakage data for Montreal WSS and that will be called **training set** is shown at Table V.10. To complete the model building, the model is tested to figure out how well it can predict new unknown data sets; this can be achieved by metrics like R^2 that identifies how close to reality or real-life scenarios the model is, i.e. the closer R^2 is to 1, the more accurate the model is.

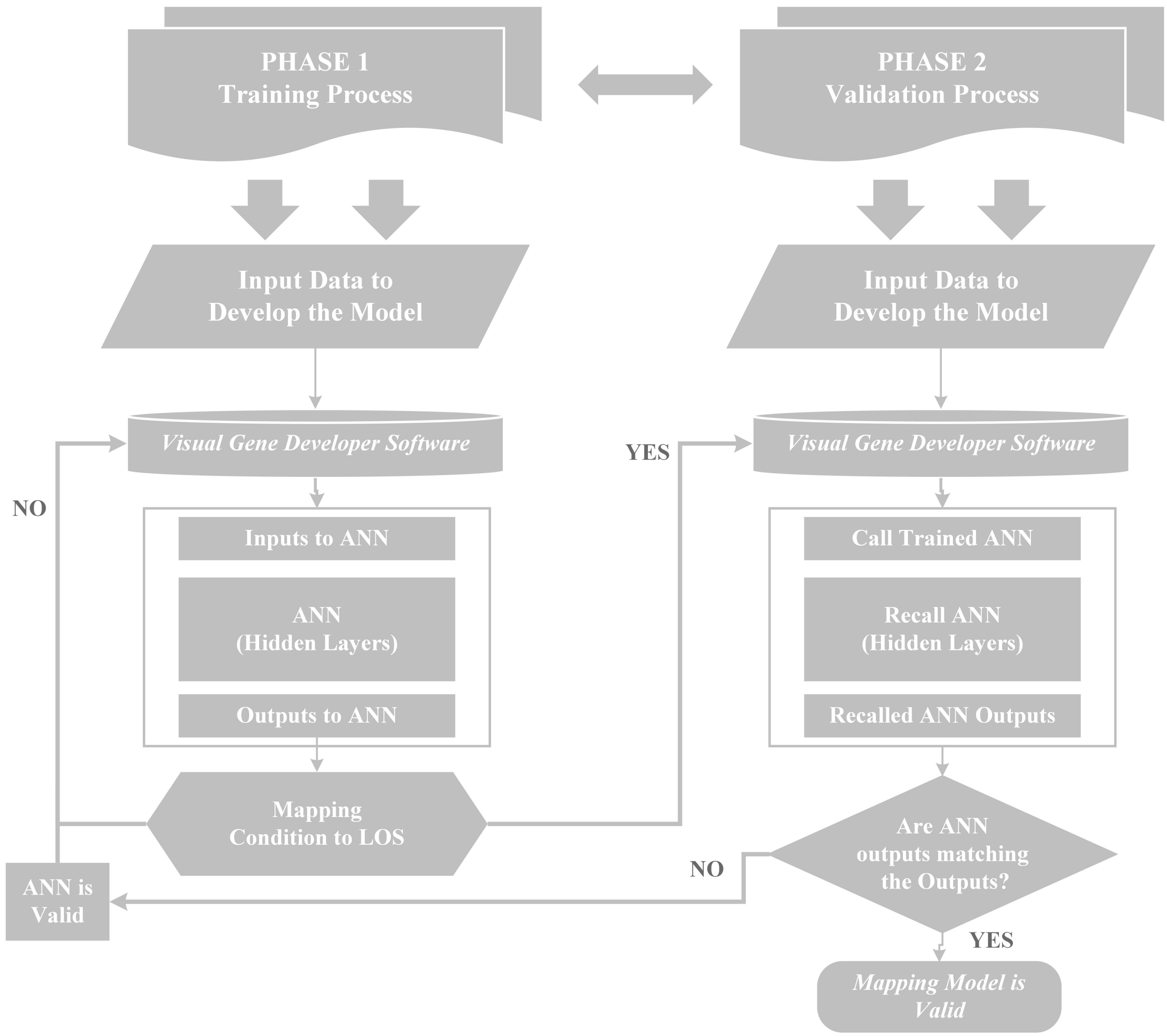

Figure III.12: The ANN Mapping Model Methodology Framework

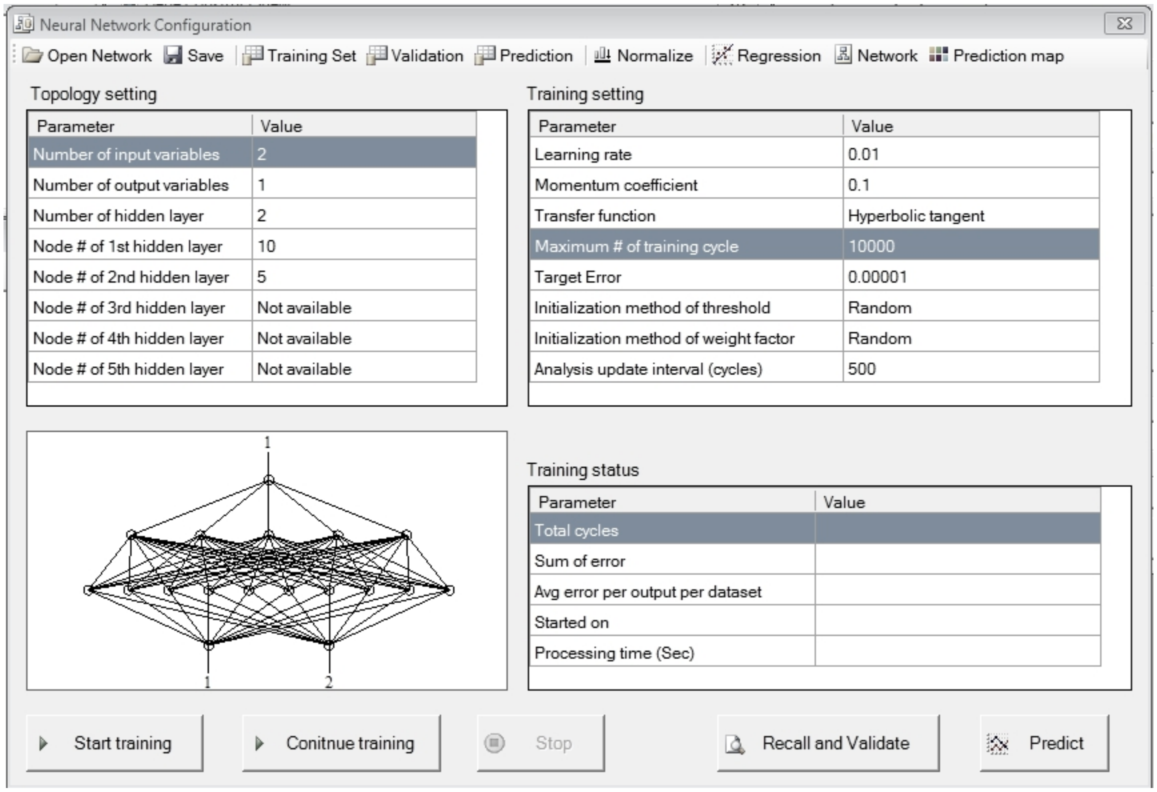

Figure III.13: Visual Gene Developer Interface for ANN

Following the training stage, the recalling or prediction stage starts, where the model can be used to predict future scenarios for different cities. A separate model must be created or trained for each city because LOS varies across different geographies. Multiple linear regression is used in developing another model, where the expression, i.e. equation, indicates the relationship between the dependent, i.e. the pipe age and breakage, and the independent LOS factors. The model validation couldn't be done because of data unavailability since the proposed approach in this research is new to utilities asset management and that lead to data scarcity of the service quality factors. However, the ANN model robustness was tested using different metrics like R^2 and the mean square error.

Chapter IV

DATA COLLECTION

To form the Level of Service hierarchy and test the developed framework, this study requires data provided by experts in the infrastructure domain. Experts from different countries, departments and agencies were contacted for their points of view on the definition of LOS and the factors for the LOS notion. So, questionnaires on the most important factors that contribute to the LOS overall score were distributed and responses were analyzed.

IV.1 Defining Factors Relative Importance

Factors were identified and ranked in two stages: In the first stage, the current PA systems and the LOS indicators in each of these systems were reviewed and then, the most comprehensive and practical factors were chosen after conducting several interviews with experts in the water industry and by including a section in the questionnaire where they can add or exclude factors that govern LOS. In the second stage, the marked factors were prioritized based on the experts' feedback in the questionnaire through pairwise comparisons; the survey respondents were also given the freedom to add or drop suggested factors. A total of 27 questionnaires were collected, 25 of which were 100% completed. The response rate was 71%. They targeted utility engineers, consultants and academics. It took the respondents 8,40 minutes on average to complete the questionnaires. Their geographical distribution and the corresponding number of respondents are as follows: Republic of Korea(1), South Africa(1), Portugal(2), Saudi Arabia(1), Egypt(1), Canada(5), France(1), Scotland-UK(1), China(1), United Arab Emirates(1), Australia(1), The Netherlands(1), The United States(4), Italy(1), Iran(1), Germany(1) and Austria(1). This distribution mainly targets developed countries since they focus on certain aspects of the Level of Service, in contrast to developing countries with a different definition of LOS due to a different set of priorities. For example, many African countries, in the developing category, give the Water Coverage factor a lot of attention because of the drinking water scarcity problem.

The questionnaire survey was conducted on two levels as follows:

1. Between the main factors with respect to the total LOS as shown in Figure IV.1. Experts are asked to make comparisons between different factors among which they choose the most and the least important ones. Experts are asked to insert how much a factor is more important than the other by choosing a value from 1 (least) to 9 (most).

2. Between the sub-factors of the (quality of supplied water) factor as shown in Figure IV.2.

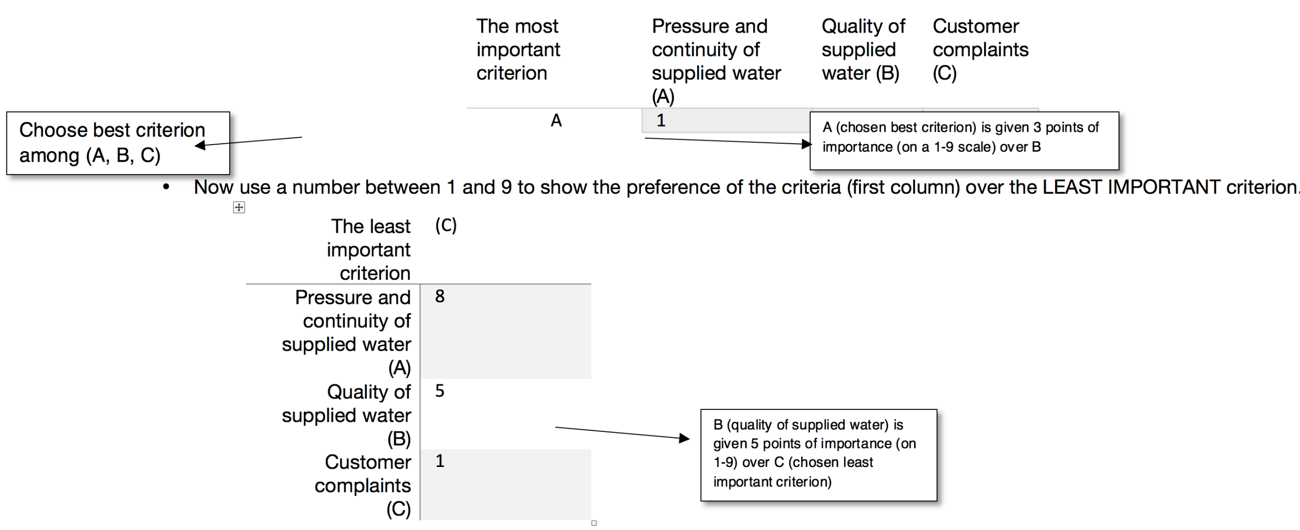

Figure IV.1: BWM Questionnaire First Level

- First level of comparisons: Level of Service (LOS) main factors which are: pressure and continuity of supply, quality of supplied water and customer complaints are compared against each other.

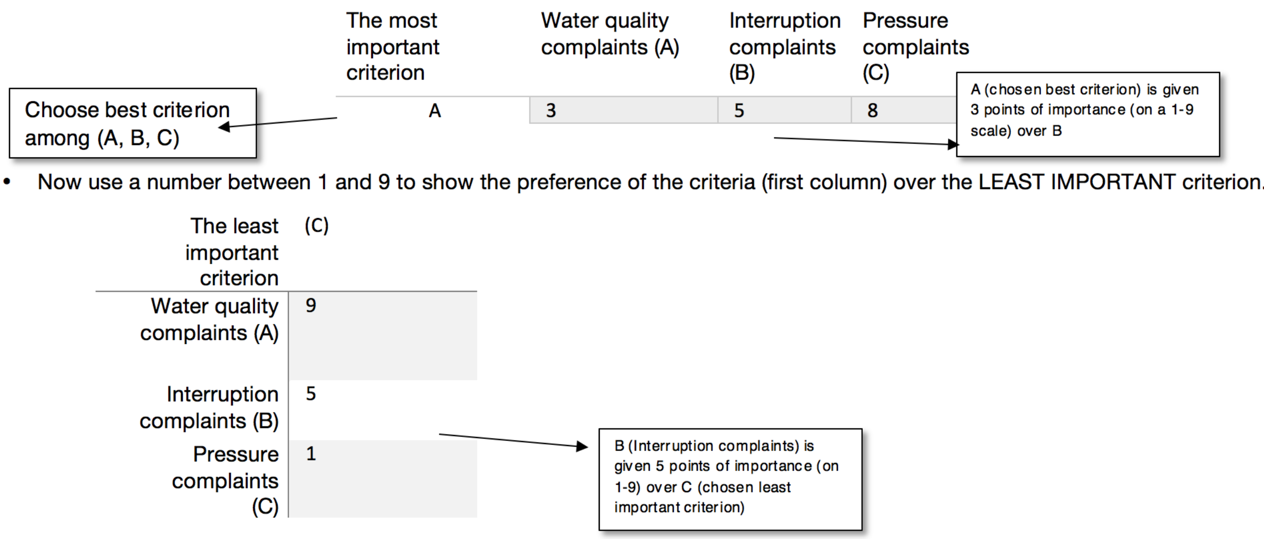

Figure IV.2: BWM Questionnaire Second Level (Customer Complaints)

- Second level: customer complaints sub-factors which are: water quality complaints, interruption complaints and pressure complaints are compared against each other.

IV.1.1 Data Analysis

A thorough analysis of the gathered responses was conducted. The difference between the relative weights obtained from the responses and the average weights was calculated, and 4 questionnaires with a high percentage of difference were excluded. In the next step, the respondents' domains of expertise are categorized into four groups, as shown in Figure IV.3: Asset Management, Water Distribution Management & Analysis, Water Quality and Water Resources Management. The respondents's domain-related experience in this study vary from 2 to more than 10 years, as shown in Figure IV.4. For the most valued factor among the LOS main factors, 64% of the respondents chose Quality of Supplied Water, followed by Pressure and Continuity of Supplied Water (27%) and Customer Complaints (9%) as shown in Figure IV.5. As shown in Figure IV.6, 77% of respondents considered Customer Complaints as the least important factor, followed by Pressure and Continuity of Supplied Water (14%) and Quality of Supplied Water (9%).

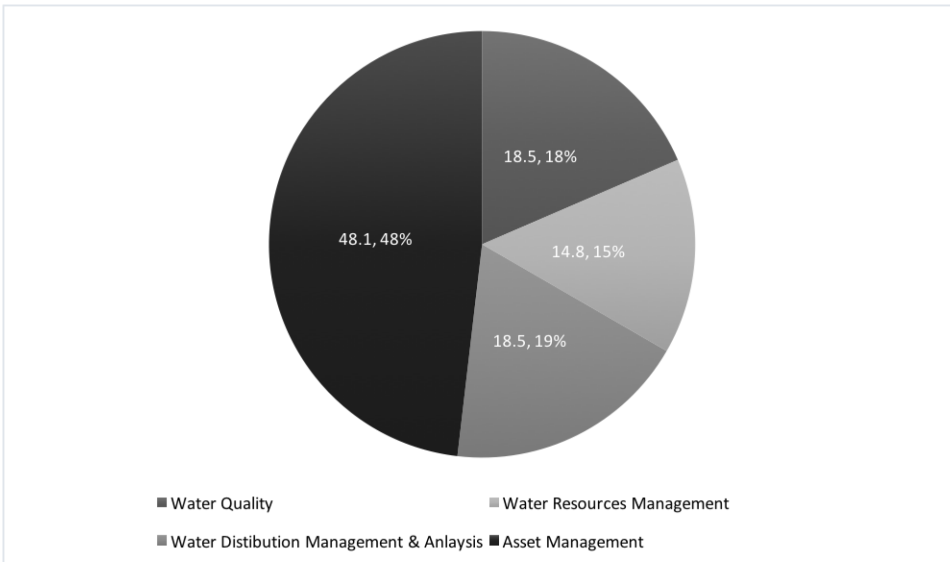

Figure IV.3: Percentage of Responses in each Domain

As is clear, most respondents realize that the most relevant aspect of the Level of Service to the customer is the quality of supplied water affecting public health and that the least relevant factor was customer complaints because of the customer's limited knowledge of the nature of service, that's why some customers issue complaints to the municipality regarding pressure or quality issues but in fact the problem is in their houses' plumbing which is irrelevant to how well the municipal water assets are performing. Respondents had the chance to add, drop or comment on the proposed factors to reach a more comprehensive definition for the Level of Service.

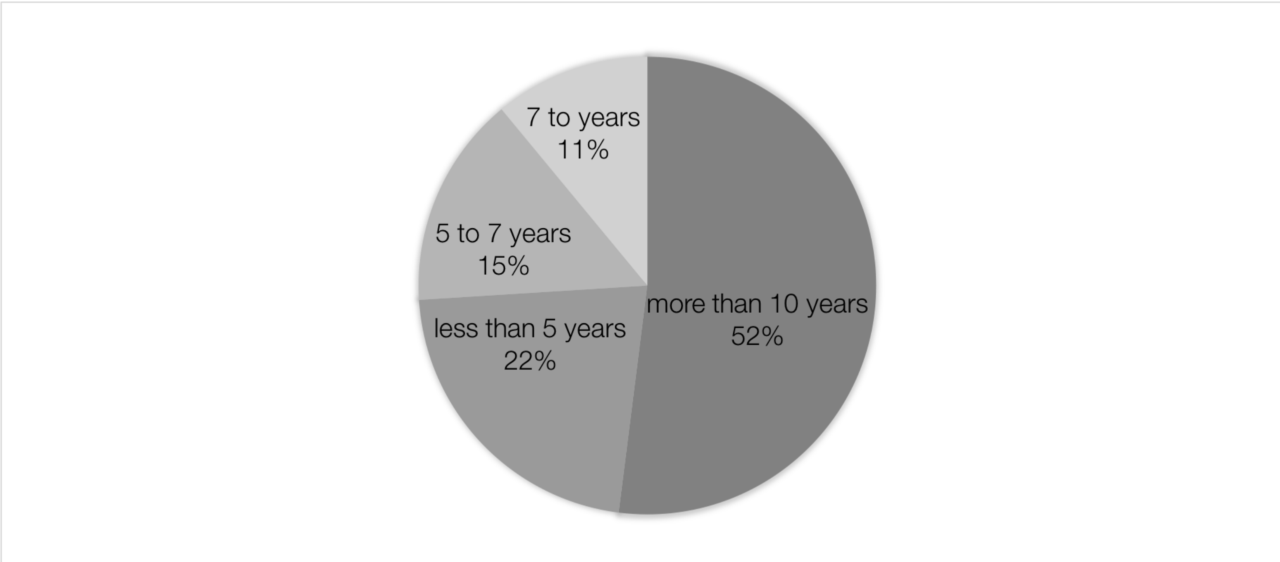

Figure IV.4: Respondents Years of Experience

According to an expert of Watershed Monitoring, Agricultural& Environmental Impacts and Aboriginal Water, about customer sense of trust in water – i.e. if they would drink the tap water – should be added. An asset manager suggested the following factors: Water Quality, Continuity of Supply and Water Loss to form the LOS model. A Municipal Maintenance engineer suggested the following factors: Pipe breakage, pipe inspection and pressure and continuity of supply. Several experts have also suggested adding Service Coverage to the proposed factors. A Water Treatment expert suggested that the governmental regulations and standards and the consumer satisfaction should be the two main factors that affect the quality of a given water supply network. An Urban Water Systems manager remarked the following: ”Sustainability of the service shall be also addressed explicitly (ISO 24510). Aspects associated with the sustainability of the service should be included: Economic, e.g. cost coverage, non-revenue water and energy efficiency; infrastructural, e.g. asset rehabilitation rate, current infrastructure fair value/asset replacement value; human resources, e.g. productivity, the sum of HR residual time to retirement/the sum of the total work life.

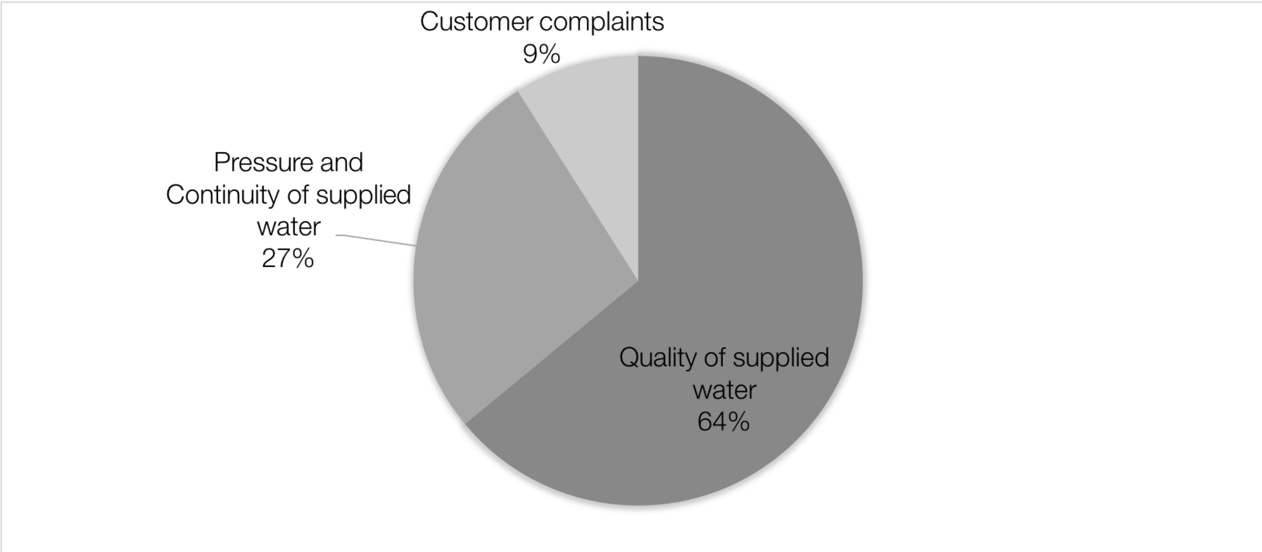

Figure IV.5: Percentages of Most Valued Factors Among Respondents

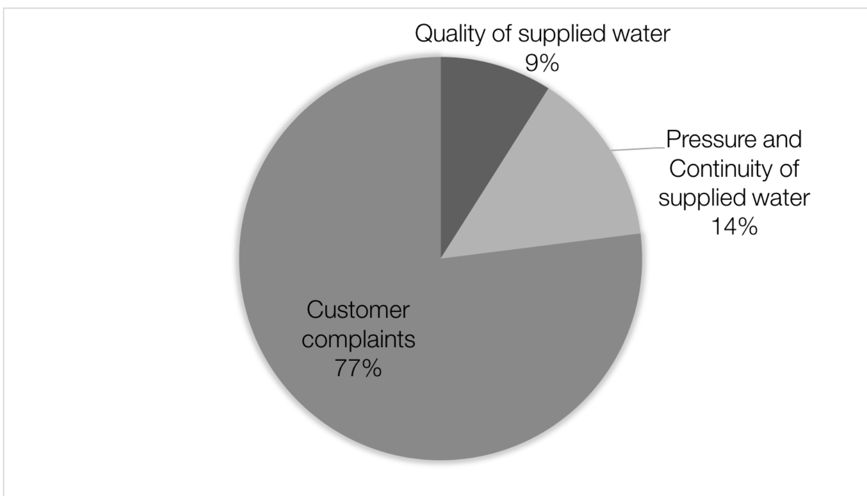

Figure IV.6: Percentages of Last Valued factors Among Respondents

First of all, customer sense was found to be a very suitable factor especially because of the gap of knowledge between the public and the experts but the factor isn't feasible because there are different theories that define customer's trust and here in the proposed framework (Customer Complaints) was proposed to satisfy the same objective. Water loss, breakage, pipe inspection are factors which are considered technical inputs that provided service depend on, thus it can't be included in the framework. Regulations and standards were taken into consideration within the framework design especially in the water quality category. Despite its importance, sustainability was ignored in the proposed model because of data scarcity, more specifically, the data related to cost coverage, non-revenue water, and energy efficiency. That is why this notion was added in the recommendations section as utility providers need to focus on sustainability as a major element for better service quality.

IV.2 Montreal WDN and the LOS Data

A set of data was collected from the Municipality of Montreal in 2014, Quebec. The WDN data include the following: Pipe age, material, size and breakage rate. The data has information about the pipelines while it does not include information about the accessories. The LOS data was extracted from a case study by a group of experts in the National Engineering Laboratory (LNEC) in the Research Technology Development (RTD) project addressing the Computer Aided Rehabilitation of Water Networks (CAREWW), published by the International Water Association (IWA). It contains a PI system with performance indicators, additional performance measures, utility information and external information èpcarew. A total of 35 case studies were used to generate LOS data for both the LOS model and the ANN model in order to fit the framework developed in this research, and the CARE-W end-users provided data to form the PI database in a close collaboration with CARE-W partners.

IV.2.1 Data Analysis

The Water Distribution Network of Montreal database include the age and breakage of all the pipes in 37 neighborhoods or zones. Averages of both breakage and age were taken as the indicators for each zone's condition as in Table IV.1 and IV.2. In order to have a thorough look into the Montreal WDN, the variance, covariance and correlation for the pipe age and breakage and were calculated. Covariance is a measure of how changes in one variable are associated with changes in the other variable. Specifically, covariance measures the degree to which two variables are linearly associated. However, it is also often used informally as a general measure of how monotonically related two variables are. Correlation is a scaled version of covariance that takes on values between $[-1, 1]$, a correlation of ± 1 indicating perfect linear association and 0 indicating no linear relationship. This scaling makes correlation invariant to changes in the scale of the original variables. If two variables are independent, their covariance is zero. However, having a covariance of zero does not imply the variables are independent, for example in some cases if two variables are jointly and normally distributed, they are independent if and only if they are uncorrelated. In this study, 2,0524 pipes were investigated for the correlation between the pipe age and breakage. As shown in Figure IV.7 the results are as follows:

- Covariance = -0.3015
- Linear Correlation = -0.2669

Table IV.1: Montreal Modified Data Set

Zone	**Age Avg.**	**Zone**	**Age Avg.**
Pierrefonds - Roxboro	35.293	Anjou	42.33
Beaconsfield	45.596	Mercier - Hochelaga-Maisonneuve	66.730
Dorval - Ile Dorval	41.866	Côte-Des-Neiges-Notre-Dame-de-Grâce	68.500
Pointe-Claire	36.029	Ville-Marie	72.189
Côte-Saint-Luc	50.570	Sud-Ouest	68.541
Villeray-St-Michel-Parc-Extension	69.285	Westmount	76.629
Saint-Laurent	40.617	Sainte-Anne-de-Bellevue	33.275
Saint-Léonard	45.721	Rosemont - La Petite-Patrie	77.577
Ahuntsic - Cartierville	62.348	Verdun	45.719
Montréal-Est	57.503	Kirkland	34.981
Rivière-Des-Prairies-Pointe-Aux-Trembles	36.204	Outremont	85.231
Montreal-Nord	53.059	Privé	84.891
Île-Bizard - Sainte-Geneviève	26.819	Mont-Royal	60.765
Plateau - Mont-Royal	81.224	Senneville	27.724
Montréal-Ouest	72.437	Dollard-des-Ormeaux	42.546
Lachine	60.349	Baie Urfé	43.988
Lasalle	46.105	Hampstead	52.845
Ministère Transport Québec	47.533	Société Transport Montréal	32.915
Montréal	46.770		

Table IV.2: Breakage Rate Averages of Different Montreal Zones

Zone	**Breakage Avg.**	**Zone**	**Breakage Avg.**
Pierrefonds - Roxboro	0.403	Anjou	0.136
Beaconsfield	0.497	Mercier - Hochelaga-Maisonneuve	0.179
Dorval - Ile Dorval	0.268	Côte-Des-Neiges-Notre-Dame-de-Grâce	0.130
Pointe-Claire	0.261	Ville-Marie	0.157
Côte-Saint-Luc	0.293	Sud-Ouest	0.158
Villeray-St-Michel-Parc-Extension	0.288	Westmount	0.161
Saint-Laurent	0.229	Sainte-Anne-de-Bellevue	0.057
Saint-Léonard	45.721	Rosemont - La Petite-Patrie	0.190
Ahuntsic - Cartierville	0.2678	Verdun	0.048
Montréal-Est	0.270	Kirkland	0.028
Rivière-Des-Prairies-Pointe-Aux-Trembles	0.190	Outremont	0.036
Montreal-Nord	0.227	Privé	0.014
Île-Bizard - Sainte-Geneviève	0.121	Mont-Royal	0.036
Plateau - Mont-Royal	0.239	Senneville	0.026
Montréal-Ouest	0.216	Dollard-des-Ormeaux	0.012
Lachine	0.192	Baie Urfé	0.00
Lasalle	0.138	Hampstead	0.00
Ministère Transport Québec	0.00	Société Transport Montréal	0.00
Montréal	0.00		

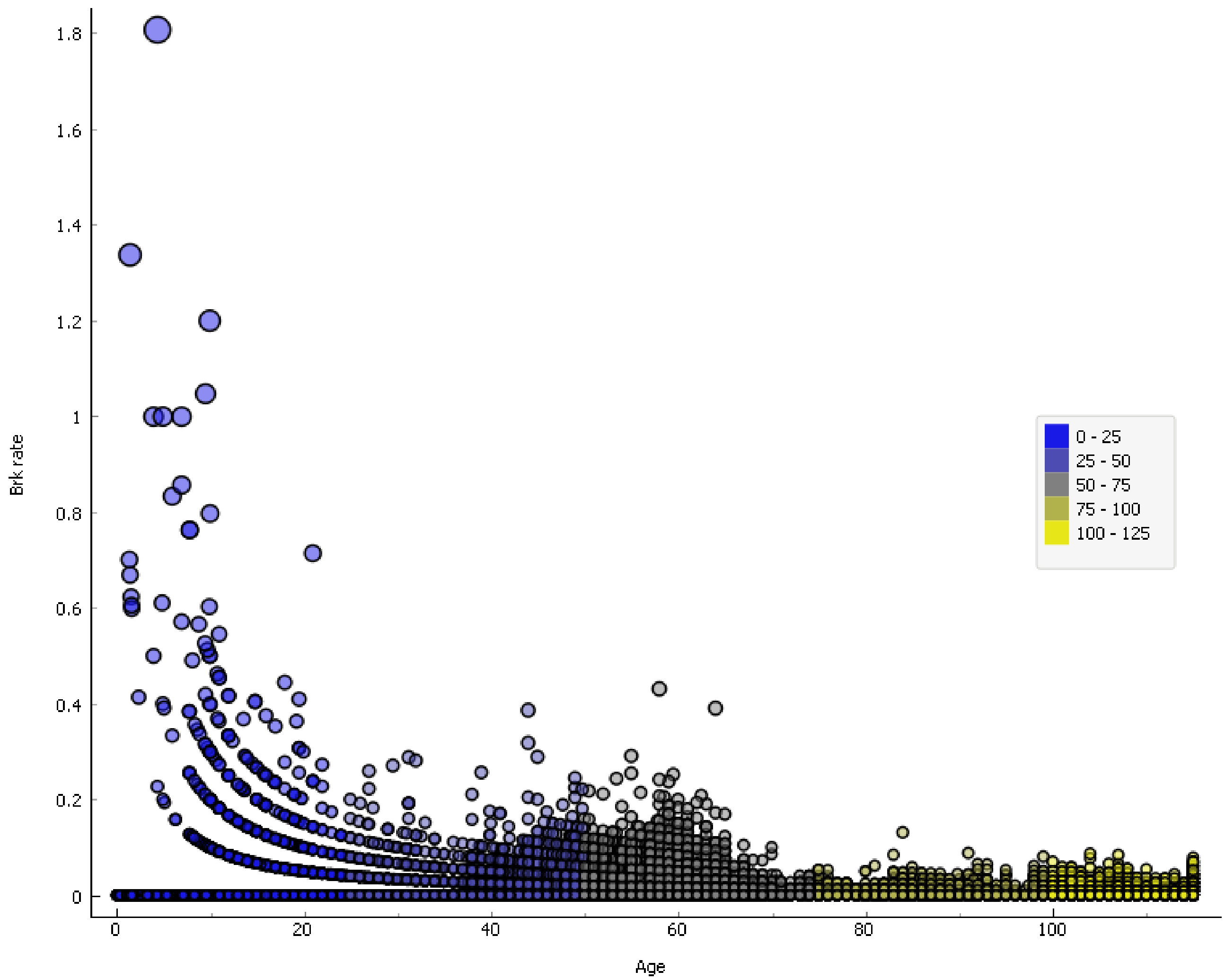

Figure IV.7: Pipe Age vs. Breakage Rate

The color of a circle reflects the age average which ranges 0 to 125 years and the size of it represents the breakage average value, i.e. the larger the higher breakage is and the results showed that most of the breakage values were from (0 - .2) breakage/year and that Montreal water network pipes ages follow a normal distribution which ranges from (0 - 125) years ; The correlation value shows a weak linear correlation between the pipe age and breakage, which implies -in this case- that breakage isn't directly affected by pipe age and that several other factors contribute to pipe breakage. The relationship between breakage and pipe material was also investigated. Figure IV.8 shows the averages of breakage rate for each material type and the corresponding number of pipes of that type in Montreal WDN .

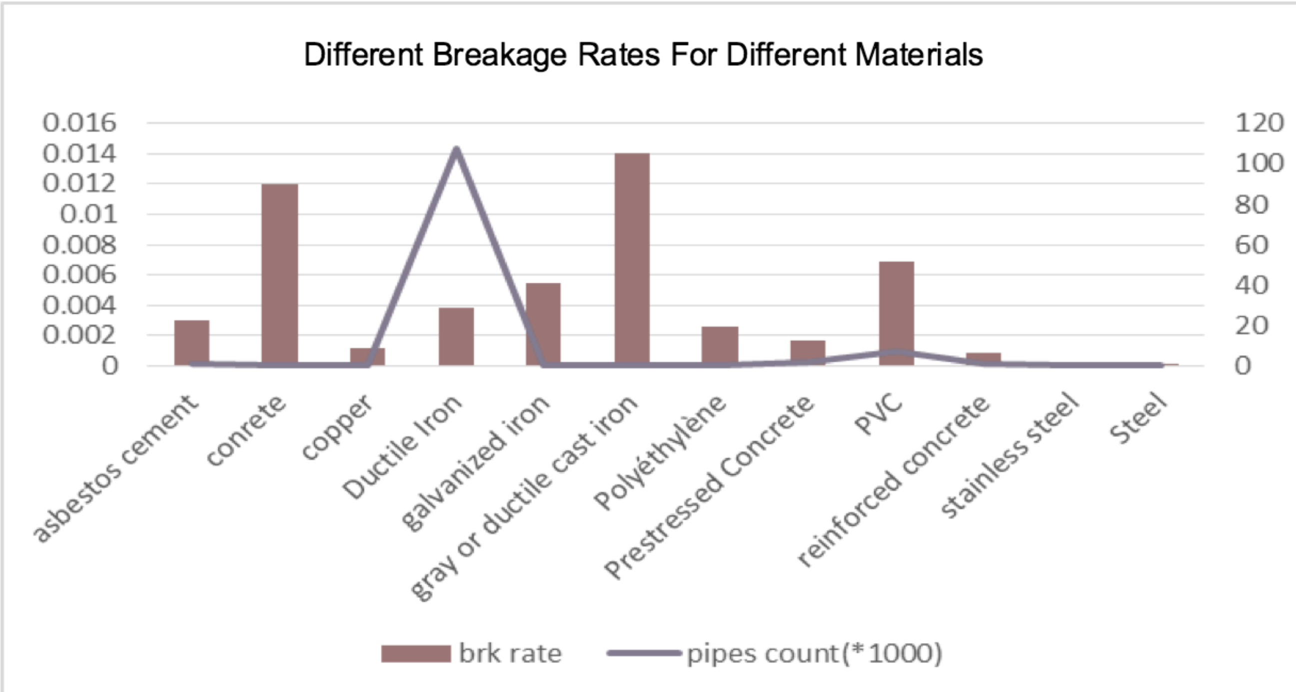

Figure IV.8: Pipe Material Type vs. Breakage Rate

Most of Montreal water network pipes are made of ductile iron followed by PVC pipes; The highest breakage rates are for the Cast Iron pipes with (0.014) breakage per year, followed by Concrete pipes (0.012) and PVC (0.07). The analysis of Variance (ANOVA) was also conducted, involving a F-test to see if the null hypothesis falls into the rejection region, i.e. to be rejected, or not. The F score/ratio is 141.663, corresponding to a 2.6098 critical value; that is why the null hypothesis was rejected, meaning that there is a statistical difference of breakage rate for different pipe materials. The variance of breakage rate over Montreal different zones was investigated as shown in Table IV.2. ANOVA results (F score=118.35, critical value=1.44) also show a statistical difference of breakage rate over different zones, which can be due to the environmental factors, traffic type and pattern of consumption varying based on the facility type, i.e. residential, industrial, etc.

Chapter V

MODEL IMPLEMENTATION

V.1 Deriving Weights of Importance with BWM

The Best-Worst Method (BWM) was used to derive weights of importance in this study. As explained in Chapter 3, seven factors affecting the LOS of WSS are identified, categorized as Customer complaints, water quality and pressure & continuity of supply. With regard to water quality sub-factors, a different weighting system was used; Pressure and Continuity is one sub-factor thus, BWM implementation is done on two levels:

1. Level of Service Main Factors (3 factors),
2. Level of Service Sub-factor (Customer Complaints) (3 factors),

A decision-maker is asked to determine the best and worst criteria to obtain their weights. Subsequently, the decision-maker is asked to indicate the preference of the best criterion over all other criteria and the preference of all other criteria over the worst criterion. The goal of BWM is to derive the weights for the criteria according to the industry expertise. The implementation of BWM is demonstrated through an example of how weight can be derived from respondent answers of the LOS main factors questionnaire, where A is the quality of supplied water, B is pressure and continuity of supply, and C is the customer complaints.

1. The respondent chose A as the best criterion and C as the worst criterion.
2. The respondent then starts rating preferences of criteria over each other by choosing a number from (1-9) to determine: the preference of the best criterion over the worst criterion (Abw), the best criterion over the third -remaining- criterion (Ab1), and the third criterion over the worst criterion (A1w) Table V.1.
3. Initial values of relative weights are assumed where the summation of them must equal to one Figure V.1.

Table V.1: Criteria Preference Rating

R1 - Abw	8.00
R1 - Ab1	6.00
R1 - A1w	6.00

Decision criteria abbreviation	Weight abbreviation	Decision criteria weight
A	R1 - w1	0.10
B	R1 - w2	0.20
C	R1 - w3	0.70

Total	1.00	Variables Constraint Met

Figure V.1: Weights Values before Optimization

4. Optimization objective is formulated by calculating the values of ($\left| \frac{w_B}{w_j} - a_{Bj} \right|$) and ($\left| \frac{w_j}{w_W} - a_{jW} \right|$) for each factor, then the maximum of both these values is taken which is 7.86; The optimization objective is the minimization of the maximum of the three maximums under the following constraints where $\sum_j w_j = 1$ and $w_j \geq 0 \; for \; all \; j$. The optimization will change the relative weights cells using genetic algorithm under the aforementioned constraints until an optimum objective is reached which was minimized from 7.86 to 4.00 Figure V.2 and V.3.

5. The optimized weights that are displayed in Figure V.4, are the results of the technique described in step (4).

Decision criteria abbreviation	$W_B/W_j - a_{Bj}$	$W_j/W_W - a_{jW}$	Max. j
A	0.00	7.86	7.86
B	5.50	5.71	5.71
C	7.86	0.00	7.86
Objective			7.86

Figure V.2: BWM Objective Formulation before Optimization

Decision criteria abbreviation	$W_B/W_j - a_{Bj}$	$W_j/W_W - a_{jW}$	Max. j
A	0.00	2.00	2.00
B	4.00	3.00	4.00
C	2.00	0.00	2.00
Objective			4.00

Figure V.3: BWM Objective Formulation After Optimization

Decision criteria abbreviation	Weight abbreviation	Decision criteria weight	
A	R1 - w1	0.60	
B	R1 - w2	0.30	
C	R1 - w3	0.10	
Total		1.00	Variables Constraint Met

Figure V.4: BWM Optimized Weights

6. The aforementioned procedure in steps 1 trough 5 is conducted on 24 other respondents. The average of the

obtained optimized Best Worst Method (BWM) weights are averaged and listed in Table V.2 for each respondent and average weights are 0.51 for the quality of supplied water (WQ), 0.34 for pressure and continuity of supply (PC), and 0.15 for customer complaints (CC).

Table V.2: BWM Derived Weights for LOS Main Factors

	WQ	PC	CC	Consistency Ratio
Variables	w1	w2	w3	
R1	.6	.3	.1	.89
R2	.5	.1	.4	1.10
R3	.5	.4	.1	.96
R4	.7	.2	.1	.76
R5	.6	.3	.1	.76
R6	.7	.2	.1	.8
R7	.2	.7	.1	.89
R8	.7	.2	.1	.89
R9	.3	.6	.1	1.15
R10	.2	.5	.3	1.24
R11	.6	.2	.2	1.16
R12	.7	.2	.1	1.05
R13	.3	.6	.1	1.3
R14	.6	.3	.1	1.07
R15	.4	.5	.1	.74
R16	.1	.8	.1	.67
R17	.7	.2	.1	.57
R18	.5	.4	.1	.92
R19	.6	.3	.1	.87
R20	.6	.3	.1	.87
R21	.6	.2	.2	.87
R22	.5	.3	.2	.79
R23	.3	.2	.5	.75
R24	.6	.3	.1	1.03
R25	.7	.1	.2	.79
Average Weight	**.51**	**.34**	**.15**	

The quality of supplied water came in the first place since customers first priority was health which is directly correlated with drinking water quality and utility performance. Pressure and continuity was chosen as the second most important factor, however, 20% of respondents considered it to be the most important factor. It is clear that most experts considered (customer complaints) as the least important factor and most of their comments included the fact that some complaints that are recorded over the last several years include irrelevant issues to the utility's performance like in-house plumbing problems which cause pressure or purity issues and that is due to the general public lack of technical knowledge of factors that govern water utility performance. Consistency ratios ranged between 1.07 and .57 ,and answers of respondents with a consistency ratio more than 1.0 were excluded resulting in having 17 consistent answers of which weights were used. This number of inconsistent answers might be due to the respondents' unfamiliarity with the questionnaire format.

V.1.1 Main Factors' Weights

The results of all respondents' weights for the LOS main weights are averaged. The average weights for each main factor are as follows:

- **Quality of Supplied Water** = .51,
- **Pressure and Continuity of Supply** = .34,
- **Customer Complaints** = .15.

The quality of supplied water is the most important factor because of the health implications that come with the degradation of this factor. Customer complaints factor was considered the least important factor by most of the respondents due to the fact that a majority of engineers receive a sizable amount of complaints on a yearly basis. The number of complaints is rendered irrelevant to the performance of the water network by the engineers due to the limited technical knowledge of the public. A sensitivity analysis was conducted to account for the uncertainty of calculated relative weights for the main factor of the Level of Service (LOS); The uncertainty accompanied with the Water Quality Factor (WQ) change ($\pm 100\%$) is the highest since it is ranging between 8.2 and 5.05 ($\approx \pm 25\%$) LOS scores, followed by Continuity of supply factor whose LOS score ranged from 7.14 to 5.05 ($\approx \pm 17.5\%$) of LOS score which corresponds to ($\pm 100\%$) change of weights, and Customer complaints has the least variation among the three factors with 5.98 to 5.05 ($\approx \pm 8\%$) of LOS score which also corresponds to a ($\pm 100\%$) weight change. Accordingly, if a $\pm 20\%$ of uncertainty was accounted, the LOS score will vary from 6.94 to 5.42 which can be considered an accepted deviation from the original values Figure V.5. The sensitivity analysis check was performed each 10 % of the previously specified range as displayed in the aforementioned figure.

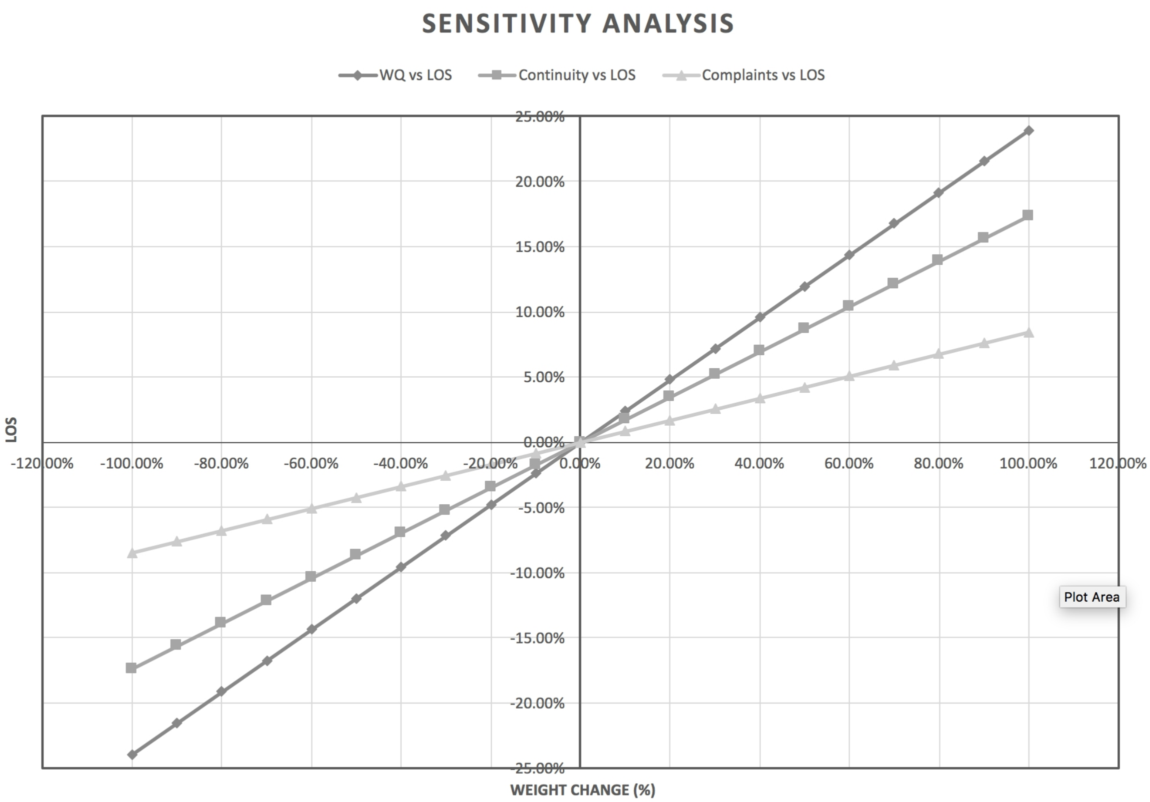

Figure V.5: Sensitivity Analysis of LOS Main Factors Weights

V.1.2 Sub-factors Weights

The same procedure is used with the Customer Complaints sub-factor except for the Water Quality factor for which a different approach is used, as well as Pressure & continuity of supply which has only one sub-factor, i.e. Service Interruptions. Weights derived from the BWM model are shown in Table V.3 where all answers were consistent (consistency ratio < 1), then averages were taken for each sub-factor. The weights of the customer complaints sub-factors are as follows:

- **Pressure complaints** = .28,
- **Water quality complaints** = .25,
- **Interruption complaints** = .20,
- **Billing Complaints** = .27.

It was noted that in the case of customer complaints types respondents gave close relative importance to each which resulted in weights of .5 difference or less. Pressure complaints were given the highest relative importance, followed by billing, water quality, and lastly interruption complaints.

Table V.3: BWM Derived Weights for Customer Complaints Sub-factors

	Pressure complaints	Water quality complaints	Interruption complaints	Billing Complaints	Consistency Ratio
R1	.4	.2	.2	.2	.65
R2	.3	.3	.2	.2	.64
R3	.1	.3	.3	.3	.62
R4	.1	.4	.4	.1	.62
R5	.2	.1	.1	.6	.64
R6	.1	.3	.1	.5	.64
R7	.2	.2	.2	.4	.78
R8	.5	.2	.2	.1	.65
R9	.4	.3	.2	.1	.65
R10	.1	.1	.3	.5	.56
R11	.6	.1	.2	.1	.47
R12	.4	.3	.1	.2	.51
R13	.3	.4	.1	.2	.65
R14	.3	.4	.1	.2	.55
R15	.3	.4	.1	.2	.54
R16	.3	.4	.1	.2	.53
R17	.3	.4	.1	.2	.52
R18	.1	.1	.1	.7	.51
R19	.1	.2	.1	.6	.5
R20	.15	.4	.1	.35	.49
R21	.2	.3	.4	.1	.48
R22	.5	.2	.1	.2	.47
R23	.4	.1	.4	.1	.47
R24	.4	.1	.3	.2	.46
R25	.3	.1	.4	.2	.45
Average Weight	**.28**	**.25**	**.2**	**.27**	

V.1.3 Water Quality Sub-factors

In order to calculate the value of the water quality factor the system of (Coliban Water) that was used included several equations that defines the value of each water quality feature. Montreal municipal drinking water report that was produced by (Lachine Drinking Water treatment plants) was used to solve Equation III.5 - III.4. Results in Table V.4 showed a variation of the water quality factor values from 2.5 to 10 which means that the worst case scenario for water quality in Montreal could lead to a score of 2.5 and 10 is the best case scenario. It is noted that the most influencing factors in Montreal are treatment plant alerts and regulatory compliance which have 250 points out of 1000. For example, Riviere-Des-Prairies zone has a score of 2.50 which is due to having 33 alerts, 10 of them are critical and a notification of regulatory noncompliance; On the other hand, Sud-Ouest has a score of 10 because all the main factors of water quality: treatment barrier effectiveness, regulatory compliance, and network protection have full scores.

Table V.4: Water Quality Scores in Montreal

Zone	**WQ Avg.**	**Zone**	**WQ Avg.**
Pierrefonds - Roxboro	4.01	Anjou	3.95
Beaconsfield	4.93	Mercier - Hochelaga-Maisonneuve	2.80
Dorval - Ile Dorval	8.50	Côte-Des-Neiges-Notre-Dame-de-Grâce	4.26
Pointe-Claire	2.52	Ville-Marie	3.52
Côte-Saint-Luc	4.56	Sud-Ouest	3.00
Villeray-St-Michel-Parc-Extension	2.50	Westmount	3.50
Saint-Laurent	7.90	Sainte-Anne-de-Bellevue	4.29
Saint-Léonard	3.05	Rosemont - La Petite-Patrie	3.73
Ahuntsic - Cartierville	5.32	Verdun	4.15
Montréal-Est	4.05	Kirkland	9.80
Rivière-Des-Prairies-Pointe-Aux-Trembles	8.60	Outremont	2.43
Montreal-Nord	3.46	Privé	3.70
Île-Bizard - Sainte-Geneviève	6.61	Mont-Royal	2.10
Plateau - Mont-Royal	2.60	Senneville	10.004
Montréal-Ouest	4.40	Dollard-des-Ormeaux	7.12
Lachine	5.50	Baie Urfé	4.77
Lasalle	3.00	Hampstead	5.51
Ministère Transport Québec	4.46	Société Transport Montréal	5.73
Montréal	2.67		

V.2 Level of Service (LOS) Score Calculation

The results of Montreal municipal drinking water produced by Lachine drinking water treatment plants report are used in the model as inputs to the LOS model. A hypothetical zone called "park A" is created to demonstrate the framework implementation steps:

1. **Water Quality:** data of the (WQ) different parameters were collected as shown in Table V.5. These values were used to solve equations III.5 - III.4 the results of which are shown in Table V.6 where each sub-category of WQ is given a score then the total of all sub-factors is divided by 100 which resulted in a WQ score of 4.95.

Table V.5: Water Quality Parameters Values

Parameter	Value
Treatment plant alerts	4
Treatment plant critical alerts	3
Health Notifications	1
E.coli (ABSENCE) percentage	100
Aluminum concentration	.144
Turbidity	.949
DPB (ug/L)	69
pH	7.4
Color	1
Coliform	98

Table V.6: Water Quality Scores

Sub-factor	Score
Treatment plant barrier effectiveness	265
Regulation compliance	0
Network protection	230
SUM out of 1000	$265 + 2230 = 495$
WQ Score	$495/100 = 4.95$

2. **Pressure and Continuity of supply:**this factors consists of one variable which is number of interruptions per 1000 connection which equals to 3 interruptions/1000 connection, this number acted as an input into the fuzzy expert system on Matlab software to calculate the output which is the effect value as shown in Figure V.6

where the output equaled 0.614 which is then multiplied by 10 to equal 6.14 out of 10 scores for pressure and continuity (PC) of supply factor.

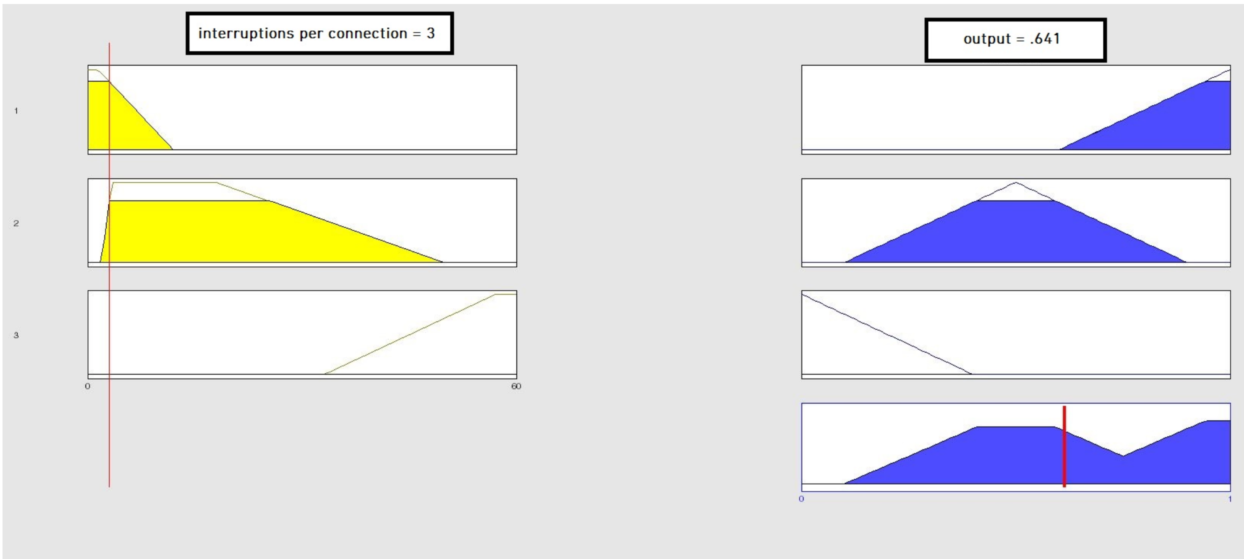

Figure V.6: Fuzzy Expert System Used to Derived the (PC) Score

3. **Customer Complaints:** which consists of three types of complaints: (1) Pressure complaints: 70 complaints, (2) Water quality complaints: 1 complaint, (3) Interruption complaints: 33 complaints; these values are also entered in a fuzzy expert system and the results are as follows: (1) Pressure complaints: 2.857, (2) Water quality complaints: 9.8, (3) Interruption complaints: 4, then each value is multiplied by its relative weight as in Table V.7 resulting in a customer complaints score of 5.51 out of 10.

Table V.7: Customer Complaints Scores

Sub-factor	Effect value	Relative weight	Score
Pressure complaints	2.86	.389	1.11
Water quality complaints	9.8	.336	3.29
Interruption complaints	4	.27	1.08
Total score	**5.48**		

4. **LOS Score:** will equal the summation of the scores of each main factor multiplied by its relative weight as shown in Table V.8 where the zone (park A) had an LOS score of 5.44.

Table V.8: Overall LOS Score Calculation

Factor	Score	Weight	Weighted score
Water quality	4.95	.51	2.525
Pressure and continuity of supply	6.14	.34	2.088
Customer complaints	5.51	.15	.83
OS overall score	$2.525 + 2.088 + .83 = 5.44$		

The model is implemented on Montreal case study following the aforementioned steps, and the results for the LOS model are shown in Table V.9.

Table V.9: Montreal Zones LOS Scores

Zone	**LOS Score**	**Zone**	**LOS Score**
Pierrefonds - Roxboro	4.31	Anjou	5.25
Beaconsfield	4.64	Mercier - Hochelaga-Maisonneuve	3.72
Dorval - Ile Dorval	5.89	Côte-Des-Neiges-Notre-Dame-de-Grâce	4.22
Pointe-Claire	4.85	Ville-Marie	4.07
Côte-Saint-Luc	5.41	Sud-Ouest	4.17
Villeray-St-Michel-Parc-Extension	4.09	Westmount	4.11
Saint-Laurent	4.62	Sainte-Anne-de-Bellevue	5.12
Saint-Léonard	4.57	Rosemont - La Petite-Patrie	2.24
Ahuntsic - Cartierville	4.35	Verdun	4.76
Montréal-Est	5.05	Kirkland	6.79
Rivière-Des-Prairies-Pointe-Aux-Trembles	6.69	Outremont	2.17
Montreal-Nord	4.41	Privé	4.82
Île-Bizard - Sainte-Geneviève	6.94	Mont-Royal	4.44
Plateau - Mont-Royal	3.55	Senneville	8.16
Montréal-Ouest	3.85	Dollard-des-Ormeaux	4.74
Lachine	4.39	Baie Urfé	5.16
Lasalle	3.72	Hampstead	5.17
Ministère Transport Québec	4.75	Société Transport Montréal	5.60
Montréal	4.64		

It is clear that zones with high quality of water had high LOS score, ex: Senneville (8.16) and Kirkland (6.79) which might be due to: (1) being fed by a treatment plant with high performance or which has an intake from a lake with minimum pollution, (2) regular and proactive maintenance approach that avoid interruptions, (3) residents are not reporting issues regarding water service; On the other hand, zones like Outrement (2.17) and Rosement (2.24) had low scores, which might be due to: (1) Polluted water sources or low treatment plant performance, (2) aging pipes which cause a high number of interruptions, lower water quality, or low pressure of water at the service point, (3) the existence of lead pipes which leaves traces of lead in the water that causes health problems especially for children. The average of LOS scores in Montreal is 4.74, maximum value 8.16, and the lowest score was 2.17.

V.3 Mapping WSS LOS to WDN Condition

The process of mapping LOS to the condition two factors, i.e. breakage and age, started with training the existing data of Montreal different zones as demonstrated in Table V.10, this happens by entering these data points into Visual Gene Developer and choosing values for ANN process parameters like: number of hidden neurons, number of layers, function type, learning rate and momentum coefficient. After that, all variables are normalized so that all variables range between 0 and 1 then the model is run for training using different settings where the following parameters were changed until the best model is reached:

1. Hidden layers format(number of neurons in each layer ((ex:5-5)) which means two layers of 5 neurons each),
2. Number of training cycles,
3. Type of the function used in the neural net.

Table V.11 shows the corresponding R^2 values with each setting and the LOS values resulted from each one are demonstrated in Figure V.7 where the black dotted line represents the actual LOS data fluctuations over different zones, the closest model to the original data was model (F) which is represented by a pink dotted line with a .871 value of R^2 and that is considered a good model for future prediction.

- Two hidden layers of 5 and 10 neurons,
- Learning rate =0.01,
- Momentum coefficient =0.1.

Table V.10: ANN Model Training Results

Zone	**Age Avg.**	**Breakage Avg.**	**LOS**
Pierrefonds - Roxboro	35.29	0.27	4.31
Anjou	42.33	0.23	5.25
Beaconsfield	45.60	0.14	4.64
Mercier - Hochelaga-Maisonneuve	66.73	0.22	3.72
Dorval - Ile Dorval	41.87	0.00	5.89
Côte-Des-Neiges-Notre-Dame-de-Grâce	68.50	0.04	4.22
Pointe-Claire	36.03	0.50	4.85
Ville-Marie	72.19	0.06	4.07
Côte-Saint-Luc	50.57	0.13	5.41
Sud-Ouest	68.54	0.40	4.17
Villeray-St-Michel-Parc-Extension	69.28	0.29	4.09
Westmount	76.63	0.24	4.11
Saint-Laurent	40.62	0.01	4.62
Sainte-Anne-de-Bellevue	33.28	0.26	5.12
Saint-Léonard	45.72	0.27	4.57
Rosemont - La Petite-Patrie	77.58	0.01	2.24
Ahuntsic - Cartierville	62.35	0.00	4.35
Verdun	45.72	0.19	4.76
Montréal-Est	57.50	0.12	5.05
Kirkland	34.98	0.11	6.79
Rivière-Des-Prairies-Pointe-Aux-Trembles	36.20	0.03	6.69
Outremont	85.23	0.06	2.17
Montreal-Nord	53.06	0.19	4.41
Privé	84.89	0.23	4.82
Île-Bizard - Sainte-Geneviève	26.82	0.14	6.94
Mont-Royal	60.76	0.24	4.44
Plateau - Mont-Royal	81.22	0.18	3.55
Senneville	27.72	0.03	8.16
Montréal-Ouest	72.44	0.00	3.85
Dollard-des-Ormeaux	42.55	0.00	4.74
Lachine	50.35	0.00	40.39
Baie Urfé	43.99	0.16	5.16
Lasalle	46.11	0.27	3.72
Hampstead	52.84	0.05	5.17
Ministère Transport Québec	47.53	0.16	4.75
Société Transport Montréal	32.92	0.16	5.60
Montréal	46.77	0.29	4.64

Table V.11: R^2 Resulted from Different Model Runs

	Momentum	Learning rate	Hidden layers format	Training cycles	Function	R^2
A	0.1	.01	5-10	10k	Hyperbolic Tangent	.741
B	0.1	.01	10-10	10k	Hyperbolic Tangent	.755
C	0.1	.01	5-10	30k	Sigmoid	.524
D	0.1	.01	5-10	30k	Gaussian	.626
E	0.1	.01	5-10	50k	Hyperbolic Tangent	.822
F	0.1	.01	5-10	100k	Hyperbolic Tangent	.871

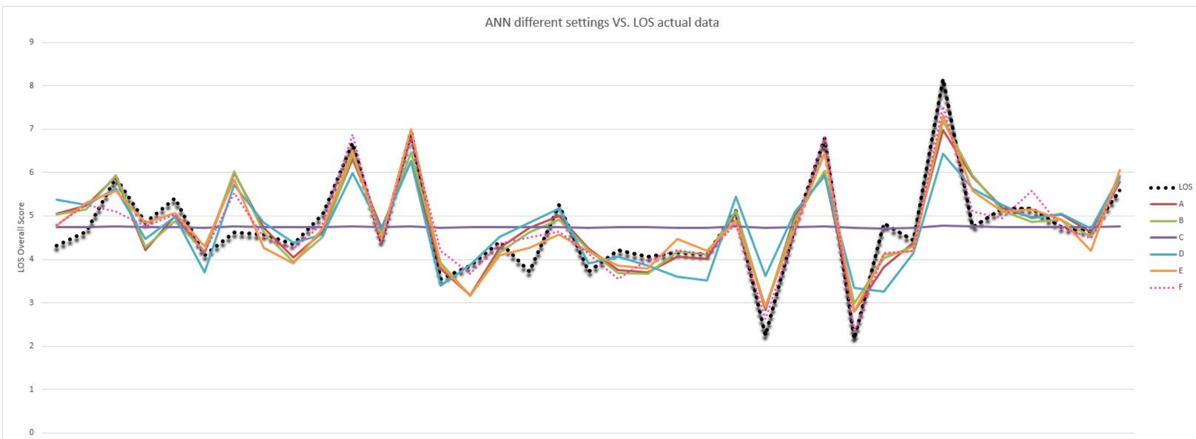

Figure V.7: Models Comparisons to Actual LOS Data

Residuals were calculated by subtracting LOS actual data from our model is LOS data and then they were compared against the inputs, i.e. age average, and breakage average, as shown in Figures V.8 and V.9 where there are no specific patterns thus, the residual plots reflect that the ANN model does not need improvement in that regard.

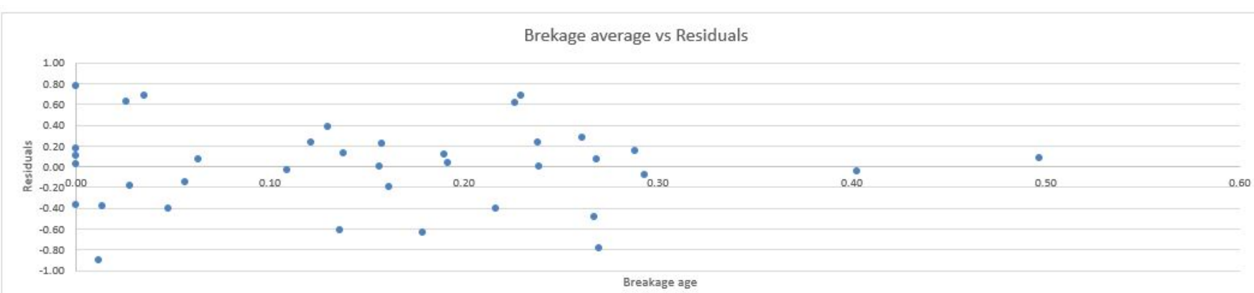

Figure V.8: ANN Residuals Compared Against Breakage Average

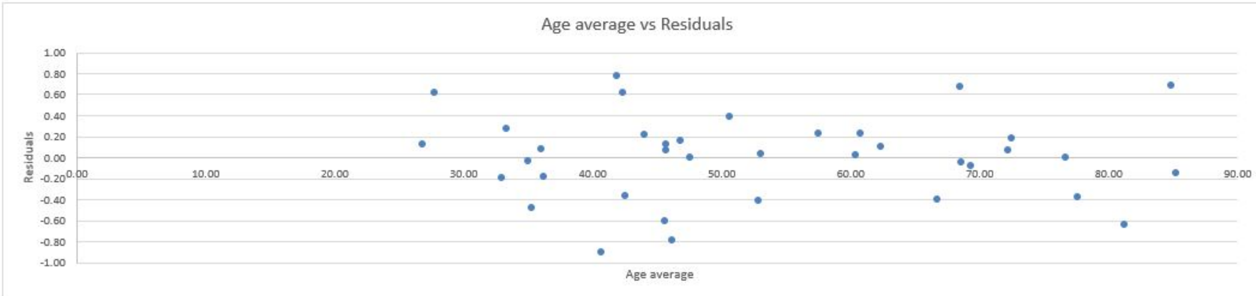

Figure V.9: ANN Residuals Compared Against Age Average

V.3.1 Multiple Regression Model

A multiple regression model is created as shown in Figure V.10 using the same dependent and independent variables in the ANN model to be compared against it; The blue line represents the original values of Montreal LOS scores, the red-colored line represents the ANN model predictions, and the green-colored line represents the regression model predictions. It is clear that the ANN model followed the original values fluctuations over different zones better than the regression model which is fairly performing in predicting LOS scores too. Analysis of variance (ANOVA) results which are presented in Table V.12 show the following:

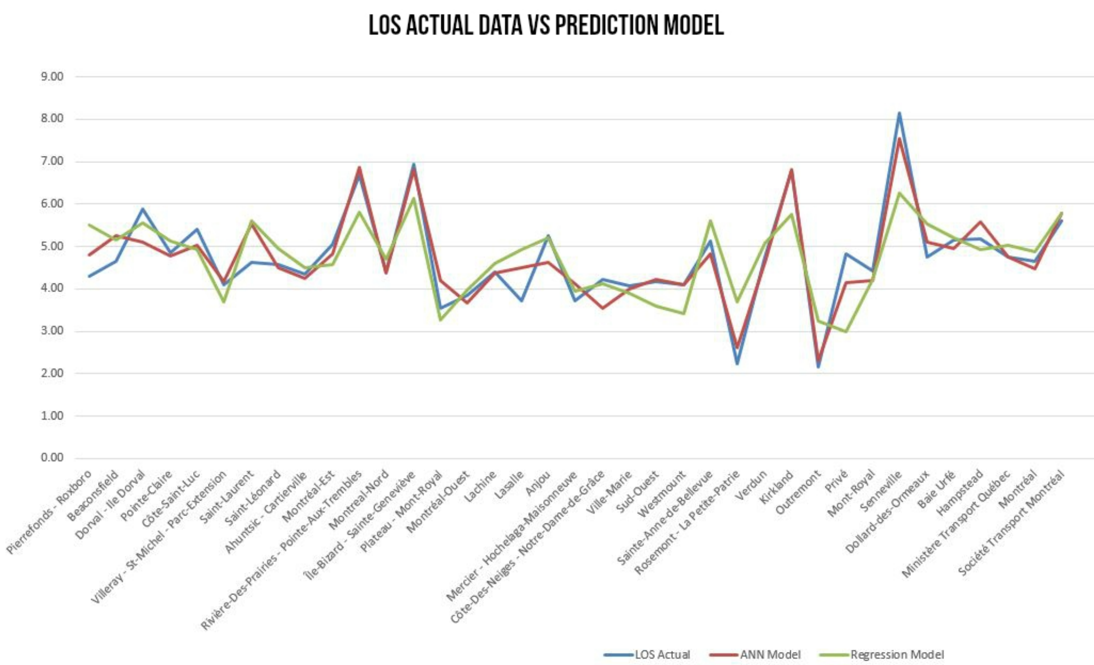

Figure V.10: ANN Model Compared Against Regression Model

Table V.12: Multiple Regression ANOVA Results

	df	SS	MS	F	P-value
Regression	2	27.37	13.687	22.99458	4.8E-07
Residual	34	20.24	.595		
Total	36	47.611			

- A degree of freedom (df) = 2 for regression reflects the number of regressors, i.e. age and breakage, the total (df) = 36 which (n-1) where n is the number of data points, and the residual (df) which is the total (df) - regression (df).
- Total sum of squares (SST) = 47.6 which measures the total variability, regression sum of squares (SSR) = 27.37 which reflects the number of squares explained by regression, and error sum of squares (SSE) = 20.24 which reflects the amount if squares not explained by regression.
- Regression mean square (MSR) = 13.6868 and mean square error (MSE) = .595; The f-statistic, also known as the F-ratio, F= MSR/MSE = 22.99 which measures the regression analysis significance and it resulted in a p-value of 4.83E-.07 which means that there is 99.9% probability that the results did not happen randomly.

The regression model results are shown in Table V.13 where R^2 equals .575 much lower than 0.871 of the ANN model which is depicted in Table V.7, this means that using ANN for this specific application gives more accurate results as seen in Figure V.10 which visualizes how ANN model could interpret the modes of fluctuation better than the regression model. Table V.14 shows the regression model results which resulted in Equation V.1:

Table V.13: Regression Model Results

	Coefficients	R^2
Intercept	7.72	.575
Age average variable	-.05	
Breakage average variable	-1.497	

Table V.14: Regression Model Output

Zone	**Predicted Y**	**Residuals**
Pierrefonds - Roxboro	5.50	-1.19
Anjou	5.20	0.05
Beaconsfield	5.16	-0.52
Mercier - Hochelaga-Maisonneuve	3.95	-0.23
Dorval - Ile Dorval	5.56	0.32
Côte-Des-Neiges-Notre-Dame-de-Grâce	4.13	0.09
Pointe-Claire	5.12	-0.27
Ville-Marie	3.90	0.17
Côte-Saint-Luc	4.92	0.50
Sud-Ouest	3.58	0.59
Villeray-St-Michel-Parc-Extension	3.71	0.38
Westmount	3.41	0.70
Saint-Laurent	5.61	-0.99
Sainte-Anne-de-Bellevue	5.61	-0.50
Saint-Léonard	4.96	-0.39
Rosemont - La Petite-Patrie	3.70	-1.45
Ahuntsic - Cartierville	4.50	-0.15
Verdun	5.08	-0.32
Montréal-Est	4.57	0.48
Kirkland	5.75	1.04
Rivière-Des-Prairies-Pointe-Aux-Trembles	5.81	0.88
Outremont	3.24	-1.07
Montreal-Nord	4.70	-0.29
Privé	3.00	1.83
Île-Bizard - Sainte-Geneviève	6.13	0.81
Mont-Royal	4.23	0.21
Plateau - Mont-Royal	3.26	0.29
Senneville	6.25	1.90
Montréal-Ouest	3.98	-0.13
Dollard-des-Ormeaux	5.53	-0.78
Lachine	4.61	-0.21
Baie Urfé	5.21	-0.05
Lasalle	4.94	-1.22
Hampstead	4.92	0.25
Ministère Transport Québec	5.03	-0.29
Société Transport Montréal	5.78	-0.19
Montréal	4.88	-0.24

$$LOS = 7.72 + (-.052 * ageaverage) + (-1.497 * breakageaverage) \tag{V.1}$$

That equation implies that both breakage and age are inversely proportional to LOS. After normalization, it is seen that breakage is multiplied by -.92 and age by -.43 which means that breakage average has a higher influence on the Level of Service (LOS) of a zone, that might be due to the fact that pipe aging is not hazardous until any break or performance inefficiency occur. Residual plots in Figure V.11 did not show any pattern for residuals and most of the points are clustered around zero which means that no improvements are needed to be made in that regard. It's also important to mention that inter-dependencies exists between factors whether for condition or level of service factors, for example, structural factors that affect the overall condition of pipes also impacts the operational factors of them such as leakage volume and losss in water pressure. The same concept exists in service quality, for example, the water quality and interruptions reflect on the number of customer complaints.

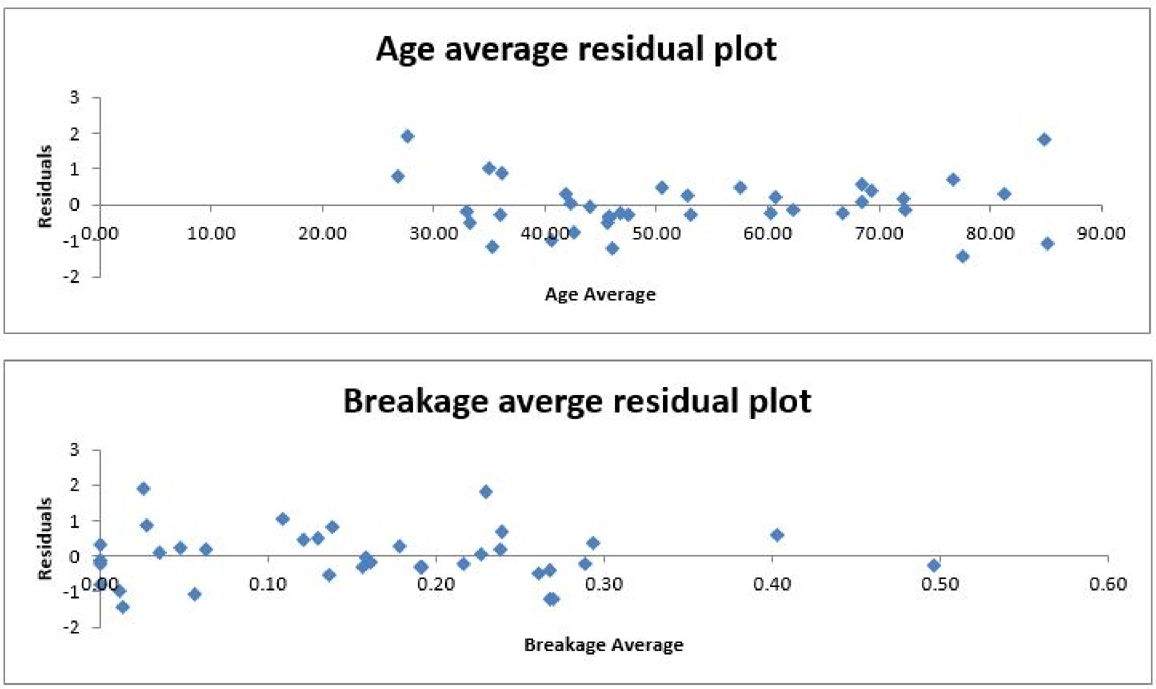

Figure V.11: Regression Model Residual Plots

Chapter VI

CONCLUSION AND RECOMMENDATIONS

This chapter summarizes the results and the efficiency of the developed framework/approach and assesses the degrees to which the research objectives were satisfied. Recommendations are then proposed for Level of Service (LOS) measurement, and suggestions are put forth for future research that could build upon this work. The methods presented in this thesis have been shown to infer different aspects of Water Supply Systems (WSS) level of service and how does it relate to Water Distribution Network (WDN) condition. By providing a framework that defines LOS, this work provides a means of developing a customer-oriented asset management system that can be used by any utility through adapting used factors to ones that fit their asset management strategy and which decipher level of service to put it into context with condition in the same framework. The developed model gives decision makers a clear idea about the impact of their maintenance activities and asset management strategies on provided service in order to have a sense of how their investment affects the public. This research demonstrates how important it is to have a customer-oriented asset management approach in place for any utility that wants to optimize it is budget when allocating it over different Water Supply System's assets. To be able to implement such an approach, there should be a mind-shift in how and what data are to be collected by different utilities, meaning that, data regarding the customer perspective of the drinking water service must be gathered such as:

- Interruption complaints, (Critical Interruptions, Populations experiencing restrictions to water service),
- Pressure complaints,
- Water quality complaints, (Water taste complaints, Water colour complaints),
- Billing complaints,
- Water quality data gathered from the network on a timely-basis not only the treatment plant's data.

Not all utilities in developed countries gather the aforementioned information and categorize them in a way that can help data analysts or utility engineers to have a thorough look in how customers perceive the service and how to sustain the level of drinking water provision service.

VI.1 Summary of Findings

The following is a summary of the work done during the development of the model:

- *The main factors that affect LOS as perceived by the customer* were identified; These factors were mounted to sub-factors which can be calculated using different formulas that contain variables.
- *Data analysis of a case study* showed that pipe breakage isn't directly dependent on it is age but there are more variables that account for a pipe breakage rate, on the other hand, an F-test was conducted which showed that breakage averages vary given different pipe materials which had also a sufficient statistical difference.
- *Best Worst Method (BWM) was used to derive the weights out of experts' opinions* that were collected using a questionnaire. Questionnaire results were analyzed and any outlier or incomplete information was eliminated.
  - Excel add-in EVOLVER® was used to optimize for the BWM equations in order to calculate optimized weights for each sub-factor.
  - Data for the water quality sub-factor were collected using Montreal's treatment plant reports.
  - Customer complaints and interruptions data were collected using a case study which was conducted by the national civil engineering laboratory in Lisbon. The case study included performance indicators, additional performance measures, utility information and external information for most of the 35 case studies that had the light shed on.
  - LOS score for Montreal different zones were calculated.
- *Artificial Neural Network (ANN) was used to create a model that predicts LOS* given information about breakage and age averages for Montreal's zones/boroughs. A multiple regression model was also created for the same dataset and then was compared to ANN in terms of R^2 value.
- *ANN showed a better representation* of the relationship between LOS and condition, having a higher R^2 value.

VI.2 Limitations

- While the methods in this thesis are largely generalizable to other infrastructure systems, the model developed in this work was designed as an inception for the development of a more customer-oriented comprehensive asset management approach. Hence, it can't be applied directly on real-life scenarios without modifications to account for different factors which reflect the level of of service of other infrsature systems.
- Since priorities vary over different geographies, factors change and need to be re-identified for different applications. For example, it is recommended that for some developing countries to exclude customer complaints and for countries with water access challenges to include (service coverage) as a factor to address the challenges that these countries have.
- This research was concerned primarily with the methodology and implementation of the above processes, and has only demonstrated a broad idea of the Water Distribution Network (WDN) condition, thus, a more thorough condition assessment model must be adopted before mapping it to LOS.

VI.3 Future Work and Recommendations

This model can be enhanced or extended in the future to be more precise and to cover more aspects. The following are some suggested future research enhancements and extensions:

VI.3.1 Research Enhancement

- The developed model utilized 37 data points and thus, in order to develop a more mature and reliable model, more data points are required by gathering more historical data to be incorporated into the ANN model to develop a more defining relationship between LOS and condition.
- To estimate a more accurate LOS model more questionnaires have to be collected from around the globe to determine the different relative weights of LOS factors.
- Exploration of more factors that represent new aspects of the customer perception of the level of service.

- Using experts opinions by conducting a questionnaire to determine the different ranges of member functions to be used while obtaining effect value of LOS factors.
- For the development of the model, assumed data was utilized. For the development of a real and more precise model, real data is reacquired from utilities to imporove the accuracy of the developed model.

VI.3.2 Research Extension

The framework developed in this thesis can enable a number of studies that require a large volume of LOS related information, and the framework itself could be improved by synthesizing it with other existing research.

- Implementation is believed to be more efficient and effective if the inputs and outputs were linked with any Geographic Information System (GIS) where the geographic and asset attribute data storage, handling and presentation capabilities of GIS can be used. Results can also be visually presented and that can make decision-making much easier especially for less technical parties.
- Social science research can be embedded into the model because the gap between both utility's and customer's must be taken into consideration while developing the model.
- Financial aspects of infrastructure asset management should be added to extend the work in order to help top-level management allocate the budget and be able to use a more comprehensive decision-making system.
- Defining a LOS for Water Supply Systems (WSSs) can be extended to include other infrastructure systems (Roads, Sewer Networks, Bridges, ..etc.) by adopting the same approach adopted here in this thesis.
- The use of big data can help municipalities develop a data-driven decision making system that is extremely responsive to changes whether regarding condition or LOS by using the recent technologies in assets condition or performance measurement to monitor the assets in real-time and even automating the decision making process itself so that actions can be taken immediately in cases of inefficiencies, expected failures or health hazards.

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