Multi-Criteria Decision Based Evaluation of Municipal Infrastructure Projects

by

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Abstract

Public and private agencies that are in charge of planning, evaluating, and executing the operation, maintenance, and renewal of assets are always faced with difficulties, such as aging assets and funding limitations. In addition, the growth of population and increasing environmental protection and preservation concerns and regulations have already put more pressure on involved agencies and organizations to establish more efficient, effective and even more sustainable investment plans. The motivation of the thesis is to assist the agencies involved in asset management to allocate their funds and resources more efficiently and cost effectively in order to provide a basis for reducing the amount of future budget requirement and keeping the assets at the same or even better condition. This research reviews the strategic goals and objectives of typical municipalities in order to identify the strengths and weaknesses of ongoing municipal asset management; an efficient and more practical decision making process at the strategic level of municipal asset management has been developed.

Infrastructure asset management entails multiple steps, processes, and management levels. A formal and typical structure management of infrastructure systems can be divided to three main levels: project level, network level (or tactical level), and strategic level. This thesis concentrates on the strategic planning that is done by senior managers in municipal governments. Furthermore, municipal infrastructure in this research is limited to pavements, bridges, water and sewer networks; however, all findings are applicable to similar type infrastructure assets.

The methodology of this research entails four main parts: preparing a comprehensive literature review of the domain, developing the decision making process, designing and conducting a survey regarding municipal priorities, analyzing the responses, and proposing and testing a suitable and practical solution for decision making for municipalities.

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I want to thank asset management group of City of Vancouver and some other Canadian municipalities for their cooperation and interests.

Dedication

This thesis is dedicated to my parents for their endless love, care, inspiration, and support along these years

Chapter 1 Overview

1.1. Introduction

Asset management can be interpreted as a strategic approach to manage and sustain assets: information describing this approach can be found in reports, guidelines, and best practices (FHWA, 1999; Victoria Government, 1995; IAM, 2008; InfraGuide, 2004). In Canada there are numerous related documents such as the National Guide to Sustainable Municipal Infrastructure: Innovations and Best Practices (InfraGuide, 2004), Model Framework for Assessment of State, Performance, and Management of Canada's Core Public Infrastructure (NRC/NRTSI 2012), Municipal Infrastructure Investment Planning (MIIP) reports (MIIP, 2010), and PAS 55 (IAM, 2008). Researchers such as Mirza (Mirza and Haider, 2004), Haas (1997), Lounis (Morcous and Lounis, 2005), and Vanier et al. (Vanier et al. 2009; Vanier, 2006; Rahman and Vanier, 2004) have written extensively on the subject in research publications.

The theme of asset management has emerged due to the needs of asset managers to deal efficiently and effectively with the challenges existing in the development and operation of infrastructure assets. Some of main challenges are low funding (Gibbins et al. 2004), involvement of too many stakeholders (Too, 2009), health and environmental regulations (CCME, 2012), cumbersome planning, and the consumption of large amounts of resources (Van der Mandele, 2006). The author of this thesis also believes that long project planning and implementation time is also a common problem that exists in complex and mid-to-large scale projects such as infrastructure works.

Some definitions of asset management from several perspectives are presented in the following chapters. For the most part, they all point to (1) business procedures, (2) engineering activities, and (3) economic analysis as the three principles of asset management. Two definitions from the Canadian InfraGuide (InfraGuide, 2004) and the U.S. Federal Highway Administration (FHWA, 1999) are presented, respectively:

> "Asset Management is the combination of management, financial, economic, engineering, operational and other practices applied to physical assets with the objective of providing the required level of service in the most cost-effective manner." (InfraGuide, 2004, p. 12)

> "Asset Management is a systematic approach of maintaining, upgrading, and operating physical assets cost effectively. It combines engineering principles with sound business

practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making.'' (FHWA, 1999, p. 7)

In this thesis, the overall objective of asset management is defined as follows: "to deliver service to users at predetermined levels of service while considering restrictions, sustainability parameters, and risk of failure."

In this regard, the asset management process is defined as a series of processes that begin with data collection and performance modeling. These processes are followed by identification of restrictions, development of alternatives, and decision-making procedures (Vanier et al. 2009). Finally, the asset management processes is completed by making decisions, taking action, and monitoring the implementation. The scope of this thesis encompasses infrastructure owned by all types of municipal governments.

1.2. Research Problem Statement and Objectives

Achievement of the entire objectives of asset management requires efficient collaboration of several sections and departments within the public works departments of organizations, accurate documentation of current condition, realistic and applicable policies and strategies, constant updating of information, and in the end, the application and use of appropriate support tools to monitor the long term performance. These factors can differ from place to place or city to city due to the city's circumstances and overall strategies and policies. Moreover, approaches of decision makers and asset managers for evaluating infrastructure projects may be different from one person to another.

The objective of this research is to provide a methodology for asset managers to compare project alternatives. The objective includes the determination of a series of criteria appropriate to both organizations and individuals for prioritizing municipal infrastructure projects. The thesis also attempts to answer the question of how asset managers can apply these criteria, or in other words, which decision analysis method can properly evaluate the projects under scrutiny. Finally, a decision-making model has been developed that can assist asset managers and infrastructure analysts to evaluate and select the priority projects more systematically.

1.3. Research Methodology

The research objectives are attained by developing a decision-making model that mimics the processes that municipalities follow in order to prioritize projects and that implements state-of-the-art research techniques to improve the quality of decision making. A series of research tasks are required to properly fulfill the objectives. These tasks are listed sequentially as follows:

a. Literature Review

b. Interviews and Surveys

c. Modeling

1.3.1. Literature Review

This thesis begins with a comprehensive literature review that includes a wide variety of topics. First, the main defining concepts of asset management are reviewed. This is followed with a review of the asset management processes of inspection and deterioration models for pavements, water and sewer pipelines. Important decision criteria that can be used in evaluating the alternatives infrastructure projects are identified.

The literature review then turns to a description of the most common types of Multi Criteria Decision Making (MCDM). This section identifies the most appropriate methods that can be applied for the selection of municipal infrastructure asset projects. Moreover, a review of fuzzy set theory is provided; this method is seen as a potential solution to deal with the uncertainties and complexities that commonly exist in real-world decision-making problems.

1.3.2. Interviews and Surveys

Decision criteria constitute one of the most important components of a decision making model, in that they need to reflect the different aspects of the decision-making problem. The challenge for the decision maker is the evaluation and then the selection of which municipal infrastructure projects should be funded: there is a plethora of decision criteria that face municipal decision makers including public health and safety criteria, established levels of service, legislated requirements, and political promises (NRC/NRTSI 2009, Vanier et al 2009).

Interviews of participants representing a number of Canadian municipalities and a web-based survey were performed as part of the research methodology. From the standpoint of this thesis, consultation with experienced persons in related fields is considered an effective way for dealing with uncertain situations and further clarifying some parts of the problem. In this regard, representatives of municipalities, academics with infrastructure management experience, and asset management consultants were chosen to participate in a web-based survey to take advantage of both theoretical and practical experience and perspectives.

1.3.3. Modeling

In this part of research, the results of first (literature review) and second (interviews and survey) tasks of this research methodology were used to select the most suitable type of Multi Criteria Decision Making Method for the problem at hand. Having determined fuzzy set theory as a prime decision-making method, this modeling section answers questions such as: what is the process?, what input data are required?, and how can fuzzy variables be applied? A set of decision criteria that resulted from the interviews and surveys are used as a part of the input data for the decision model.

Chapter 2 Literature Review

2.1. Definition of Asset Management

Asset management can be defined as a combination of three main areas, namely: business procedures, engineering activities, and economic analysis. All three must be coordinated to achieve the targeted objectives of an asset or a network of assets efficiently and cost effectively. A large amount of research effort has been carried out on different aspects of asset management. Each one has its own definition of asset management, which is not necessarily consistent or similar, but they all include the main concepts of asset management. In order to provide an initial insight in this field, a summary of researchers' and practitioners' definitions of asset management is provided in this section.

The Government of the State of Victoria in Australia (Victoria Government, 1995, p. 2) defined asset management as a "set of processes including the process of guiding the acquisition, use and disposal of assets to make the most of their service delivery potential and manage the related risks and costs over their entire life."

The Institute of Asset Management's definition (IAM, 2008, p. 2) is "systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risk and expenditures over their life cycles for the purpose of achieving its organizational strategic plan."

The Institute of Asset Management (IAM 2008) in the UK adopted a business approach and explained that asset management is comprised of disciplines, methods, procedures, and tools to optimize the whole life business impact of cost performance and risk exposures of the company's physical asset.

The Canadian InfraGuide (InfraGuide, 2004, p. 12) defines asset management as: "The combination of management, financial, economic, engineering, operational and other practices applied to physical assets with the objective of providing the required level of service in the most cost-effective manner".

Some researchers also preferred a holistic view for the definition of asset management. For example, Too (2008), Craig and Parrish (2003), Brown (2004), and Sklar (2004) support this approach and generally they all described asset management as an integrated business process designed to optimize the use of a utility's assets while balancing the varying needs of key stakeholders.

McNeil (2000) explained that most of the USA's State Departments of Transportation are still working to clarify what asset management means, as well as to figure it out whether the approach taken is what they really need or if it still require more revision.

Some of the following definitions of asset management presented by American and Canadian Departments of Transportation are listed below:

''Asset Management is a strategic approach to managing transportation infrastructure. It focuses on business processes for resource allocation and utilization with the objective of better decision making based upon quality information and well defined objectives.'' (AASHTO, 2006, p. 1)

Transportation Association of Canada (TAC) also adopted a business approach toward the asset management that this business strategy mainly consists of people, information, and technology (TAC, 1999). Additionally, the overall objective of asset management from TAC's perspective is to allocate the available fund effectively and efficiently among valued and competing assets (TAC, 1999).

And finally, a more comprehensive definition of asset management offered by The Federal Highway Administration (FHWA, 1999, p. 7) was selected for this thesis:

"Asset Management is a systematic approach of maintaining, upgrading, and operating physical assets cost effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making.''

2.2. Definition of Infrastructure Asset

The scope of this research relates to managing municipal infrastructure assets. Too (2009) has highlighted numerous concerns: the ambiguity of the term "Infrastructure", clarification needed of infrastructure terms and concepts, and the need for a generic classification of physical and non-physical infrastructure. Resolutions to these questions are presented in this section.

For example, Salman (2010) and Howes and Robinson (2005) explained that the term ''infrastructure'' incorporates a wide range of concepts that have already has been widely applied in many different fields like business, political science, military, information technology, etc. Too (2009) emphasized the importance of infrastructure services through their impact on social and economic development. Stevens et al. (2006) provided a more detailed description of infrastructure asset impacts on social and economic sectors, claiming that these impacts provide a foundation for virtually all modern-day economic activity, constituting a major economic sector in their own right, and raising the standards and quality of human lives is their social effects.

Salman (2010) described what infrastructure means in the civil engineering arena, which is a collection of physical systems or facilities to deliver essential public services.

The Public Sector Accounting Board (PSAB 3150, 2009) has a definition of infrastructure and other municipal assets. From PSAB's perspective, municipal assets that are referred to as "tangible capital assets" include electrical power, water and sewer network, waterways, gas and liquid fuels, telecommunications, public transit, ports, roadways, equipment and vehicle all used within municipalities operations, etc. (Vanier et al. 2009).

In summary, the definition of infrastructure provided by PSAB 3150 is very concise, precise, and closer to the scope of this research. For these reasons, this thesis adopts the definition of infrastructure and municipal assets presented by PSAB 3150.

2.3. A Short History of Asset Management Development

Stapelberg (2006) indicated it had been during the privatization of water utilities in Great Britain in the 1980s that ''asset management'' was comprehensively adopted for the first time. Too (2008) points out that the Australian Accounting Standard Board issued the Australian Accounting Standard 27 – AAS27 in 1993 and that was a way of applying asset management principles into the public works. ANAO (1996) described the concepts and principles of asset management in Australia for the first time; it had been formalized by the Australian State Treasuries and the Australian National Audit Office (ANAO 1996). ANAO (1996) defined asset management as "a systematic, structured process covering the whole life of an asset". Too (2008) added that thereafter, other Government bodies and industry sectors In Australia tried to develop, refine and apply the concept of asset management and these movements caused asset management to emerge as a separate and recognized field of management during the late 1990s. Government organizations and industry practitioners made primary contributions to the evolution and advancement of Infrastructure Asset Management (IPWEA, 2006; ANAO, 1996; Austroads, 2002; LGV, 2004; NSW Treasury, 2004; Queensland Government, 1996).

During the last fifty years, highway agencies in the United States of America have moved their primary focus with respect to asset management several times (Pantelias, 2005). These changes of approaches during this period of time can be divided into two main groups which are described by AASHTO (1999) as follows:

1. From 1960s to the mid 1980s; a shift from expansion to preservation was adopted.

d. From the mid 1980s to the beginning of the new century; the primary focus has been on employing good and sound business practices

In the end, as Stalebrink and Gifford (2002) indicated, asset management had already been widely accepted by the private sector worldwide and was already being practiced since the mid-1990s by transportation agencies in the UK, Australian and New Zealand.

Even though there was not any systematic approach for asset management in the past, there are still lots of questions about what asset management really means today (Too, 2008). The Governmental Accounting Standards Board (GASB 2001) in the United States of America issued GASB Statement 34 in 1999 which dictated basic financial statements for state and local government. Pantelias (2005) has indicated that this can be assumed to be a milestone in the development of asset management in the USA.

2.4. Why Multi-Criteria Decision Making

There are advantages of systematic decision making in any discipline ranging from medical research to engineering projects (Figueira et al., 2005; Radojevic et al., 1997; Jugovic et al., 2006; Morais and Almeida, 2007; Silva et al., 2010; Hajkowicz and Collins, 2007; Queiruga et al., 2008; Geldermann et al., 2000; Al-Rashdan et al., 1999). This becomes more tangible when some unexpected events occur or more restricted limitations are placed on decision makers and stakeholders. However, much progress has already been made in establishing effective and, at the same time, practical decision making or decision aid methods in real world situations.

Generally decision making methods can be categorized into two broad groups: outranking methods of alternatives and optimizing desirable parameters or factors. For example, more popular methods like cost benefit analysis, multiple criteria decision making, linear and non-linear optimization methods, and dynamic programming, as well as newer methods such as Genetic Algorithms (GA) and Artificial Neural Network (ANN), can be mentioned. Now, the question is how and on what basis can a suitable or potentially successful method be selected. This section attempts to find an answer to this question; more specifically, how to choose a decision-making method that addresses the appropriate investment allocations for maintenance, repair and rehabilitation of municipal infrastructure systems and networks.

2.4.1. Selection of a Decision Making/Aid Method

The selection of a suitable decision making method, from the point of view of this thesis, can be assumed as a challenging and complex process that generally requires effective consultations among decision makers. Sometimes, collaboration between decision makers and the appropriate persons from all level of organization needs to be carried out to cover all aspects of a specific decision making problem. Additionally, some parameters of the problem depend on the nature of the problem and the existing experience of the participants and the available technology should be considered. Based on the experience and opinions of the author of this thesis that are based on personal experience and knowledge gleaned from the literature review, a series of steps representing a framework have been developed to replicate a typical decision making process.

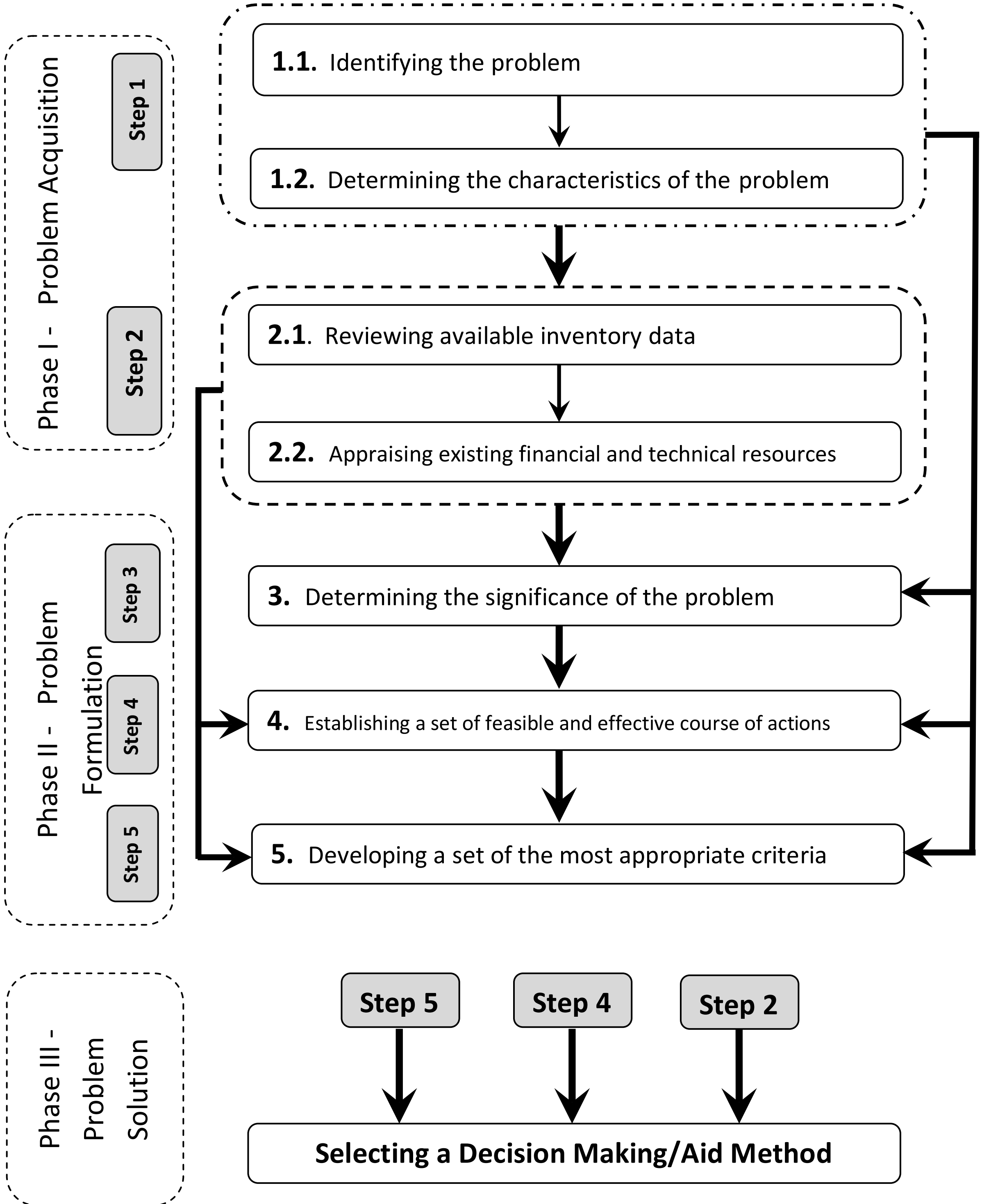


Figure 2.1. Proposed framework for selection of a decision making/aid method

Step 1 (including step 1.1 to step 1.2), as shown in Fig. 2.1, is to identify the problem and then try to identify its major characteristics. For example, the breakage of a water main and degradation of a pavement condition are the characteristics of problems that may happen, as are the corresponding complaints received by the city. For example, some initial information about the problem would be where it is located, how much water is leaking from the pipe, and approximately how many users are affected by this problem. These data would provide an overall picture of the situation that requires a decision to be made.

In the scope of this research, the general problem is how to allocate the limited budget for Maintenance, Repair, and Renewal (MR&R) of municipal water, sewer, and pavements facilities while meeting the predetermined goals and objectives.

Step 2 (including step 2.1 to step 2.2) is to determine what information is currently available and what type of data are required. After identifying the problem and its characteristics in step 1, it is time to clarify the other side of the situation and the problem, as well as to assess the existing techniques, knowledge, and experience that can be applied to solve the problem. In the domain of asset management, this information mainly can be categorized as inventory data, such as the assets' current age, performance, remaining service life, and replacement value. Other types of information vary depending on the situation or technical and financial potential of an organization such as what are the amount of available budget and under what circumstances it can be extended. Other questions may rise such as whether the involved organizations and their personnel have already done a project or handled a similar condition before (i.e., what is the existing technical and managerial experience and background). These data are applied in the following steps which finally lead to selecting a decision aid method.

Step 3, as shown in Fig. 2.1, is to demonstrate the importance and significant of the problem. This process builds upon the previous two steps. On one hand, a general picture of the situation and characteristics of the problem as discussed in first step and, on another hand, the capabilities of the organization to deal with the problem as described as the second step. By doing so, the short and long term outcomes of problems are investigated in order to determine the significance of the problem. The outcomes can be made more explicit by providing an example. The condition, expansion potential, and overall design of infrastructure systems and networks have a great impact on the social and environmental situation of the region or area in which they are located. Furthermore, it has been widely accepted that infrastructure systems can play a vital and exclusive role in the economic growth of a province or a state (Mirza and Haider, 2004) and even in the overall Gross Domestic Product (GDP).

All in all, this information indicates that the aging of infrastructure should be considered as a highly important challenge that can cause profound changes in the social, environmental, and economic condition of a municipality. In addition, more elaborate decision making methods and analysis are required to be adopted and applied in order to provide a better and more efficient plan for the aforementioned problem (Vanier, 2006).

Step 4 is to establish a course of action or alternatives to deal with the problem based on the information obtained from previous steps (the characteristics and significant of the problem and the financial and technical resources available).

Step 5 is the last and the most important step of selecting a suitable decision-making technique. During this step, a set of criteria are developed in order to evaluate the established alternatives more systematically. In other words, these criteria provide a standardized and acceptable environment in which the effectiveness and efficiency of feasible alternative can be assessed.

The proposed framework in Fig. 2.1 shows schematically a general process of selecting a decision-making method and the relationships between its five steps. In addition, as shown in this framework, this process is separated into three major phases in order to provide a better understanding of the content of the steps, to emphasize the sequence of the process, and to illustrate how they can be organized, collaborated, and performed to finally deal with the problem. These three phases are: 1. Problem Acquisition, 2. Problem Formulation, and 3. Problem Solution.

As the proposed framework shows in Fig. 2.1, Step 1 and 2 are categorized as Phase 1, Problem Acquisition. It includes any activity related to understanding a problem, the existing information, and the potential of an organization belongs to this phase. In the next phase, Problem Formulation, the importance and several aspects of problem are identified and feasible and effective alternatives as well as appropriate criteria for analyzing the alternatives are provided. At the end, the third phase of the framework selects a method or methods to assess the efficiency and effectiveness of the alternatives in a systematic manner. Although the last phase has been named ''Problem Solution'', it does not mean that the selection of a method to aid the decision making process can solve a problem alone. Indeed, this phase can include other steps, summarized as follows:

- Running the selected decision aid method and obtaining a first version of results
- Analyzing the result and providing an interpretation

- Verifying the obtained result relative to the predetermined objectives of the organization
- Revising the result or a part of the decision-making method if necessary
- Finally, as the last part of dealing with a problem such as a decision-making situation, provide an implementation plan by considering the finalized outcomes of the decision making process

All of the steps constituting the third phase of dealing with budget allocation problems among municipal infrastructure networks are shown in Fig. 2.2.

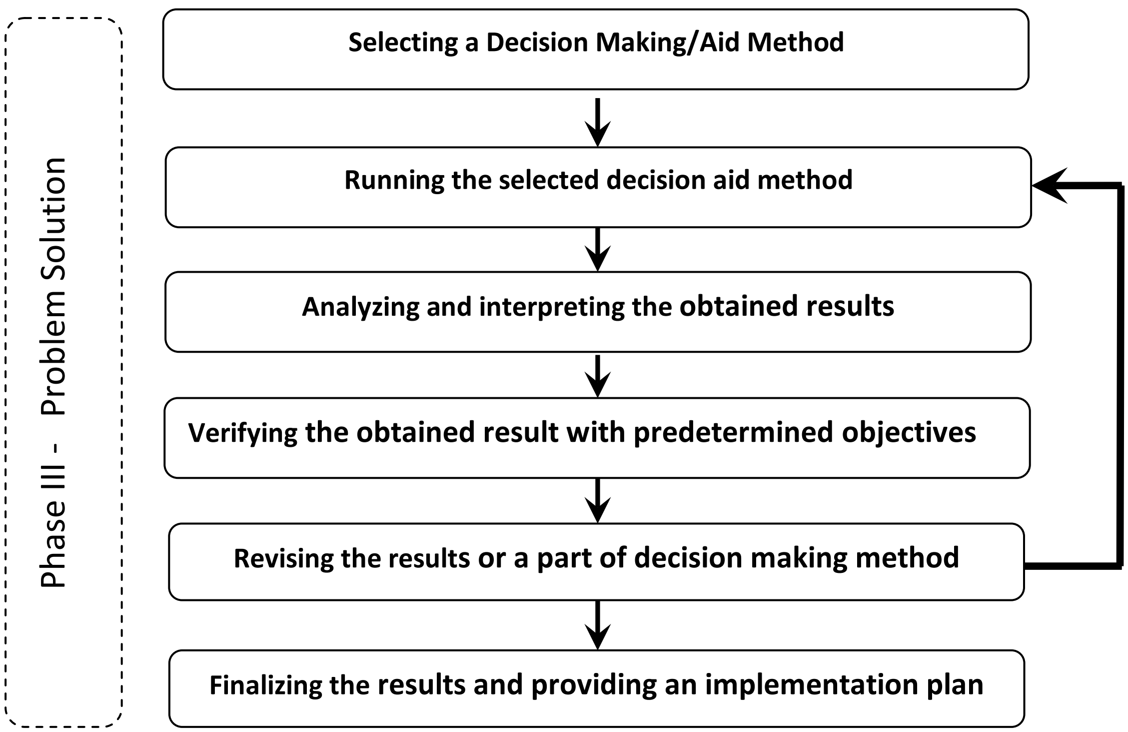


Figure 2.2. Several components of phase III of the proposed framework

To conclude, it is partially true that all steps of the proposed framework shown in Fig. 2.1 can play a role in choosing a decision-making method. However, the second, fourth and fifth steps significantly affect the final selection. In fact, the characteristics and nature of criteria and alternatives, as well as the significant of the problem, may have more compatibility with some methods rather than others. In this sense, this proposed framework considers these three steps as the main elements or criteria to select a decision-aid method.

2.4.2. Multi-Criteria Decision Making and Infrastructure Asset Management

This section outlines the capabilities of Multi-Criteria Decision Making (MCDM) and the applicability of this decision aid in infrastructure asset management. As noted earlier, one of the main challenges facing government agencies and private companies owning a diverse portfolio of assets is how to allocate a limited budget efficiently and cost-effectively among infrastructure assets. Multiple constraints such as technical feasibility and limited financial resources turn this type of decision into a complex problem which has many conflicting objectives. However, the owners of infrastructure systems are often municipalities who also are in charge of operating these facilities as well as implementing any maintenance and rehabilitation actions. So, considering the other responsibilities that a municipality may have and the complexities of existing municipal facilities, decision-making methods should not be overly-complicated or impractical. Additionally, complex tools generally require more detailed data, ranging from inventory data to social and environmental information for a region, which exacerbates problems with their practicality. Two important guidelines, then, are that data collection is an expensive process that imposes additional costs, and that many municipalities suffer from the lack of a coherent database system to store asset inventory data. Moreover, as with any software or decision-support tool development, it is important to recognize who the users are and what their knowledge level is. For the scope of this research, the users are defined as senior and junior asset managers, who possess several years of professional experience. As a result, any tool must be straightforward in its use, besides offering good functionality and efficiency, in order to increase the acceptance of the tool by users.

As pointed out in the proposed framework, each decision generally is composed of two major parts: criteria and alternatives. In the arena of infrastructure systems, the criteria are indicators of objectives and goals; unfortunately, these multiple objectives can be in conflict with each other. For instance, simultaneously balancing the social, environmental, and economic aspects of each of the alternatives in a decision is challenging and conflicting. The question remains of how a decision-aid method can be made to work with these conflicting criteria and, at the same time, have the potential to show users how these criteria can be applied with each other. The major objective of the decision problem of allocating the budget among municipal facilities is to balance between important criteria such as environmental and economic factors in order to rank the projects.

Multi Criteria Decision Making (MCDM) is a comprehensive and user-friendly method that is popular for both academic research and real projects. As such, practitioners may place more trust in its results than in more complex and newer methods like dynamic programming or genetic algorithms, which are much less known to most practitioners. In addition, MCDM allows users to formulate the problem in the way they want. That is, MCDM allows users to establish multiple discrete alternatives that can accomplish the objectives of an organization. Since the outcomes of MCDM are relationships among these user-defined alternatives with respect to the criteria, the results are easy for users to interpret. MCDM is also capable of applying the conflicting criteria, and it is fairly easy to change parameters or functions at any time. The method has this ability to be combined with other methods such as the use of fuzzy variables. Furthermore, MCDM is one of major analysis and decision-making tools to be applied to work with spatial data (e.g., in conjunction with Geographic Information Systems, GIS), particularly for selecting the location of a project. Fig. 2.3 summarizes the major characteristics of Multi Criteria Decision Making Techniques to show why these methods have been selected in this research and, more generally, why they are popular in infrastructure asset management and many other fields. The following section reviews the literature relating to MCDM in greater detail.

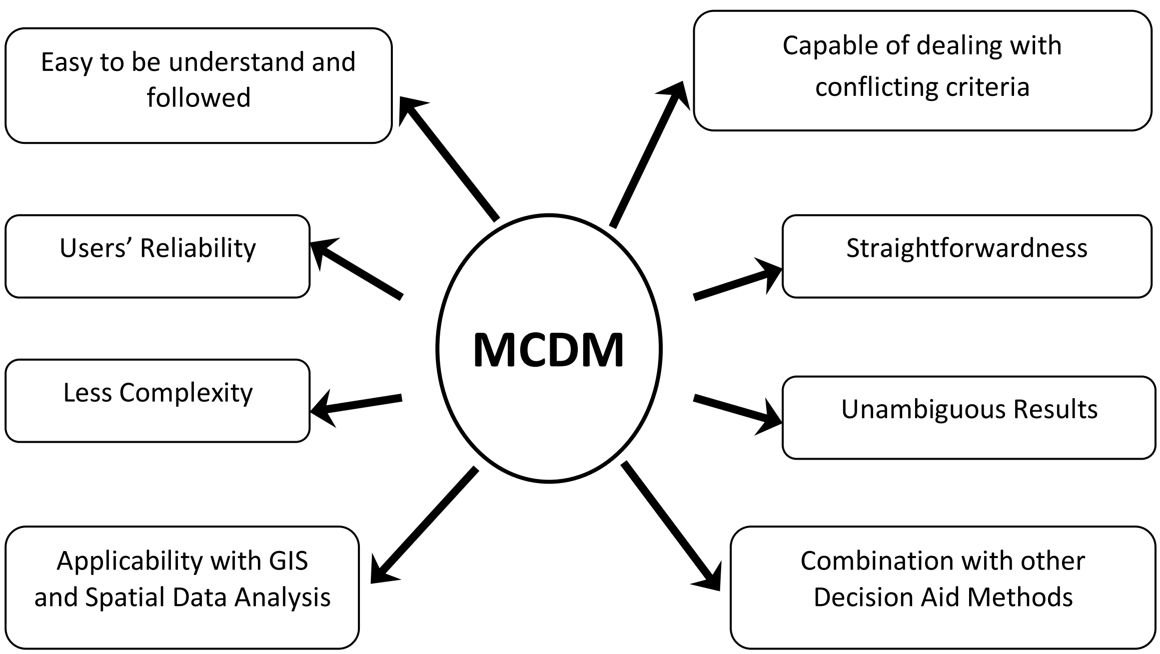


Figure 2.3. Major characteristics of MCDM being applied in decision making problems for infrastructure assets management

2.5. Introduction to Multi-Criteria Decision Making Techniques

Several Methods of Multi Criteria Decision Making have been developed to date; they can be classified into different groups by considering or emphasizing specific features of methods, decision makers' approaches, and characteristics of the problem environment. One of the most popular classifications of MCDMs is to group these into Multi Attribute Decision Making (MADM) and Multi Objective Decision Making (MODM) (Farahani et al., 2010; Kahraman, 2008 b; Mendoza and Martins, 2006; Rao, 2007). The notable differences between MADMs and MODMs relate to different treatment of objectives, decision variables, and alternatives.

MADM are decision-aid tools that are applied when the problem is to select an alternative. The alternatives in MADM problems are finite, there is a set of predetermined courses of action that is being evaluated, and there are a discrete number of decision variables.

MODM problems, on the other hand, seek a solution that meets constraints and the decision maker's objectives and preferences, where the decision variables may be continuous and the number of alternatives may be large or infinite.

Malczewski (1999) presented more detailed differences between MADM and MODM than those indicated by Hwang and Yoon (1981) and Zeleny (1982), as shown in Table 2.1. These differences range from the definition of each part of the decision making method to the size of the problem and the control of decision makers.

Table 2.1. Comparison of MADM and MODM approaches (Malczewski, 1999)

Criteria for comparison	**MADM**	**MODM**
Objectives defined	Implicitly	Explicitly
Alternatives defined	Explicitly	Implicitly
Number of alternatives	Finite (Small)	Infinite (large)
Attributes defined	Explicitly	Implicitly
Criteria defined by	Attributes	Objectives
Constraints defined	Implicitly	Explicitly
Decision maker's control	Limited	Significant
Decision modeling paradigm	Outcome-oriented	Process-oriented
Relevant to	Evaluation/choice	Design/search

Besides classifying the different methods of MCDMs into MADM and MODM, there are other types of MCDM. As noted earlier, these classifications can relate to specific parts of the problem or characteristics and process of MCDM methods. For instance, these MCDM methods have been classified based on features of information (Hwang and Yoon 1981), application of the methods (Belton, 2002; Mendoza and Martins, 2006), and the cognitive processing level (Jankowski, 1995). Fig. 2.4 depicts a taxonomy of 14 different types of MADM methods by considering the type and importance of information (Hwang and Yoon 1981). The classification is based, first, on the type of information which can be obtained from decision makers and, second, on the salient features of the obtained information.

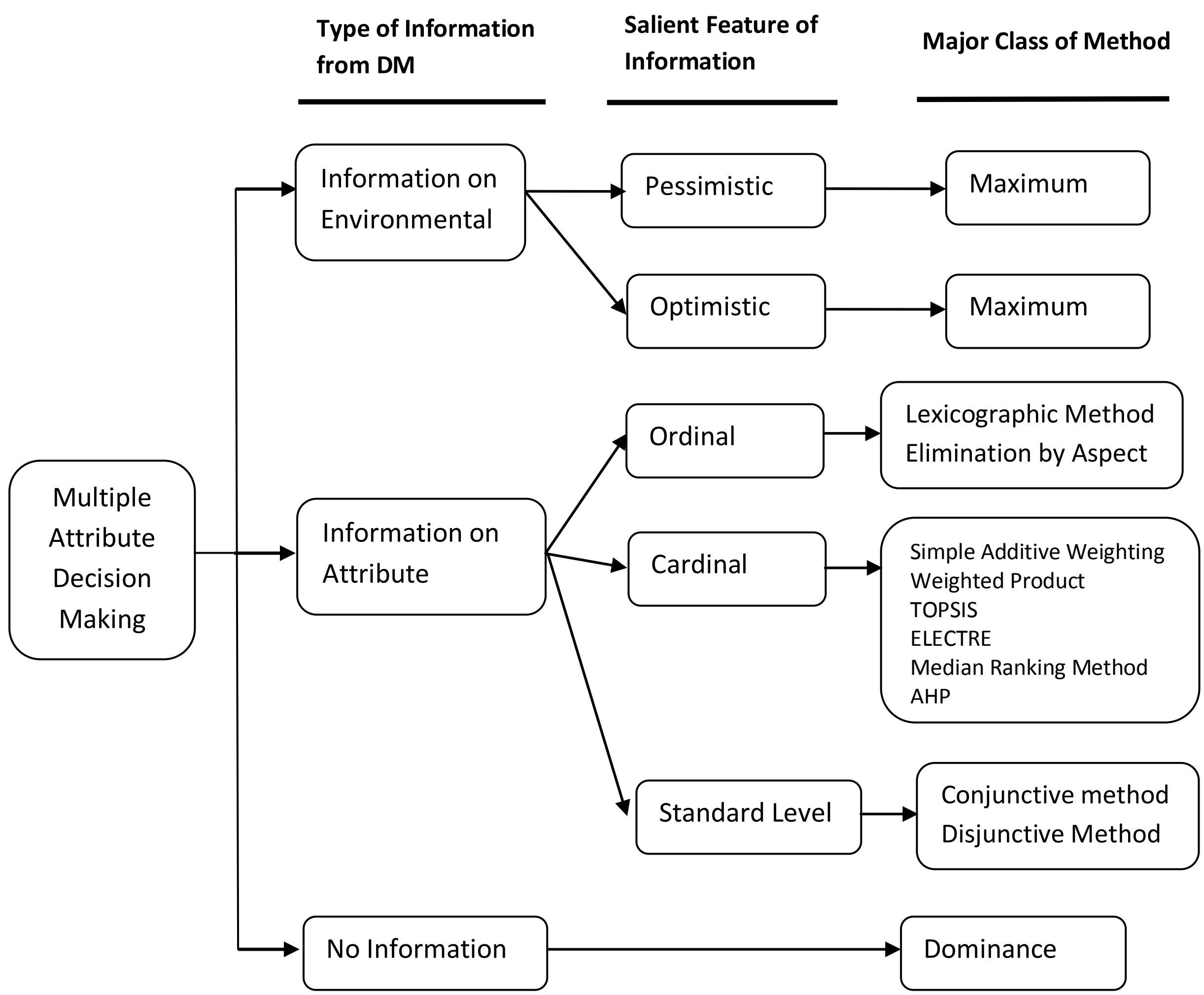


Figure 2.4. Taxonomy of MADM methods (Adapted from Hwang and Yoon, 1981)

2.5.1. Weighted Sum Method

The simplest method of MCDM is the Weighted Sum Method (WSM), which has been widely used (Rao 2007, Triantaphyllou 2000). The mathematical formulation of this method is simple and just limits calculations to the sum weighted scores of a decision matrix, as follows:

$$A_j = \sum_{i=1}^{n} w_i \, e_{ij} \qquad \textit{Equation 2.1}$$

Where A_j, w_i, e_{ij}, and n denote the WSM value of each alternative, weight of criterion i, score of alternative j with respect to criterion i, and number of criteria, respectively. In this method, alternatives can be ranked based on their WSM scores and the best alternative has the highest value (in the case of maximization).

2.5.2. Weighted Product Method

The concept of Weighted Product Method (WPM) is similar to WSM with the only difference that the addition function is replaced by a multiplication function, as in Equation 2.2.

$$A_j = \prod_{i=1}^{n} (e_{ij})^{w_i} \qquad \textit{Equation 2.2}$$

Where A_j denotes the WPM value corresponding to alternative j, and w_i, e_{ij}, and n denote the weight of criterion i, score of alternative j with respect to criterion i, and number of criteria, respectively. The alternative with the highest WPM value is considered to be the best choice (in the case of maximization).

2.5.3. Analytic Hierarchy Process

Analytic Hierarchy Process (AHP) is a commonly used and well-known method of MCDM that was developed and defined by Saaty (1977; 1994; 2000). AHP arranges the essential elements of a problem such as decision alternatives, attributes, and objectives into a hierarchical format.

A typical example of hierarchical structure using an AHP process is shown in Fig.2.5; which displays a three level representation of an overall goal, attributes/objectives, and alternatives/options.

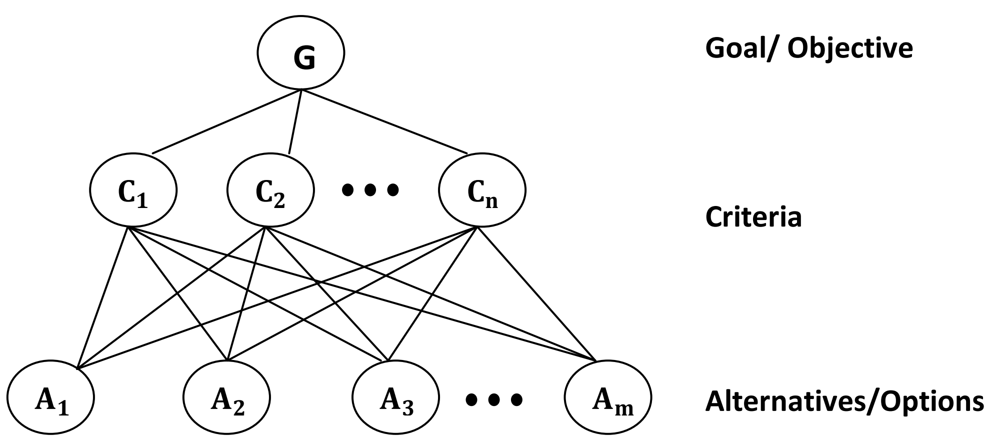


Figure 2.5. Schematic presentation of hierarchical format of AHP

Many researchers have discussed the benefits of depicting the environment and main components of a decision making problem in a hierarchal structure. As an illustration, Tavana and Hatami-Marbini (2011) indicated that by taking advantages of the hierarchy format of AHP, complex and ill-structured problems can be simplified. Dyer and Forman (1992) also pointed out the applicability of this AHP structure in group decision making. Chen et al. (2009) added that, in addition to the decomposition of a decision making problem, AHP has two more principles: comparative judgment and synthesis of priorities. Comparative judgment in AHP includes the pair-wise comparison of all elements within a given level of the hierarchical structure (Chen et al. 2009). As Saaty (2000) described, it is easier for decision makers to compare two things rather than comparing all things together in a list.

Rao (2007) defined four steps representing the procedure of solving a problem by the AHP method:

Step 1: Identify the objective and the most appropriate and effective evaluation criteria to achieve the objective.

Step 2: Assign the relative importance (weight) to evaluation criteria with respect to the objective. It can be determined by pair-wise comparison of each pair of criteria and considering the objective function.

Step 3: Determine the performance score of alternative for each evolution criterion. This process includes the comparison of the alternatives with respect to how much better they are in satisfying each criterion.

Step 4: Compute the overall performance scores for the alternatives by multiplying the relative normalized weight (w_i) of each attribute (obtained in step 2) with its corresponding normalized performance score for each alternative (obtained in step 3), and summing over the criteria for each alternative.

$$A_j = \sum_{i=1}^{n} w_i \, e_{ij} \qquad \textit{Equation 2.3}$$

2.5.4. Preference Ranking Organization Method for Enrichment Evaluations

2.5.4.1. Introduction

Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) is a MADM method that is used for ranking feasible alternatives. This method was developed by Brans (1982), extended by Brans and Vincke (1985), and there is currently a family of PROMETHEE methods, each of which has a specific application and properties that are discussed later in this section.

2.5.4.2. Application Areas

PROMETHEE has been successfully applied in many fields (Behzadian et al., 2010) ranging from medicine and health care research (Figueira et al., 2005) to engineering and financial topics that relate to the domain of civil engineering, such as transportation (Radojevic et al., 1997; Jugovic et al., 2006), water resources management (Morais and Almeida, 2007; Silva et al., 2010; Hajkowicz and Collins, 2007), and environmental engineering (Queiruga et al., 2008; Geldermann et al., 2000; Al-Rashdan et al., 1999). Reasons can be found in the research literature to justify the widespread utilization of PROMETHEE; for example, Brans and Mareschal et al. (2005) favoured the mathematical properties and user-friendliness of the process and Bufardi et al. (2008) indicated PROMOTHEE's is able to deal with incomparability between alternatives as well as being easy to understand and to use. As noted earlier, multiple types of PROMETHEE have been developed, as shown in Table 2.2 (Figueira et al., 2005; Behzadian et al., 2010). According to Behzadian et al. (2010) and Figueira et al. (2005), each member of PROMETHEE family has a specific application domain.

Table 2.2. Application of different PROMETHEE methods

Name	**Application**	**Developer**
PROMETHEE I	Partial ranking	J.P. Brans (1982)
PROMETHEE II	Complete ranking	J.P. Brans (1982)
PROMETHEE III	Ranking based on interval	Brans et al. (1986)
PROMETHEE IV	Ranking in the case of continuous solution	Brans et al. (1986)
PROMETHEE V	For problems with segmentation constraints	J.P. Brans and B. Mareschal (1992)
PROMETHEE VI	For representation of the human brain	J.P. Brans and B. Mareschal (1995)
PROMETHEE GDSS	For group decision- making	Macharis et al. (1998)
PROMETHEE TRI	For dealing with sorting problems	Figueira et al. (2004)
PROMETHEE CLUSTER	For nominal classification	Figueira et al. (2004)

2.5.4.3. Mathematical Formulation and Process of PROMETHEE

In this section, the different steps of solving a decision-making problem by means of PROMETHEE II are described. PROMETHEE is based on decision makers' preferences; it leads to a preference function by application of pair-wise comparisons, as shown below.

$$P_j(a,b) = F_j\left[\,d_j(a,b)\right] \quad \forall\, a,b\, \in A\,, \qquad \textit{Equation 2.4}$$

$$0 \le P_j(a,b) \le 1 \qquad \textit{Equation 2.5}$$

$$d_j(a,b) = g_j(a) - g_j(b) \qquad \textit{Equation 2.6}$$

Where, *a* and *b* denote two alternatives; $g_j(a)$ and $g_j(b)$ denote valuation of *a* and *b* with respect to criterion *j*, respectively; d_j denotes the differences between these two values. F denotes the preference function and $P(a,b)$ also denotes the preference of *a* with respect to *b* in the case of maximization of criterion *j*. In the case of minimization the preference functions will be transformed into:

$$P_j(a,b) = F_j\left[-\,d_j(a,b)\right] \qquad \textit{Equation 2.7}$$

Vincke and Brans (1985) proposed that six types of criterion functions can deal with most of the practical applications and they only need a few parameters which can be identified by decision makers. These six criterion functions namely are (1) usual criterion, (2) U-shape criterion, (3) V-shape criterion, (4) level criterion, (5) V-shape with indifference criterion and (6) Gaussian criterion. These six types are particularly easy to define. The mathematical and graphical presentations of these functions are provided as Fig. 2.6 where $x = g_j(a) - g_j(b)$, *K(x) = P(a,b)* if *x ≥ 0*, and *K(x) = P(b,a)* if *x ≤ 0*.

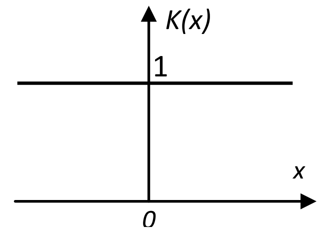
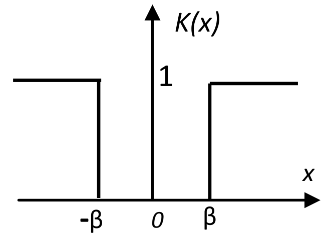
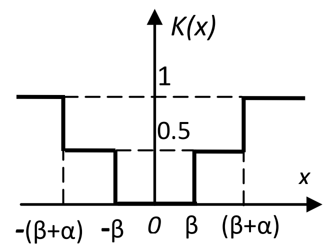
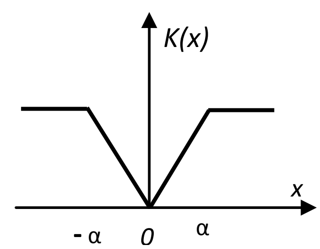
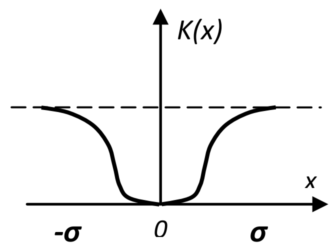
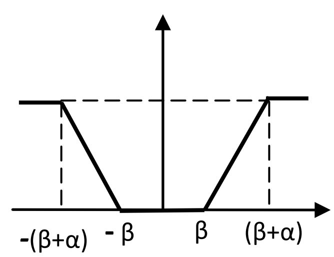
Type of criterion		Shape
1. Usual	$K(x) = \begin{cases} 0 & if\ x = 0 \\ 1 & if\ \lvert x \rvert > 0 \end{cases}$	
2. Quasi	$K(x) \begin{cases} 0 & if\ \lvert x \rvert \leq \beta \\ 1 & Otherwise \end{cases}$	
3. Level	$K(x) \begin{cases} 0 & \lvert x \rvert \leq \beta \\ 0.5 & \beta < \lvert x \rvert \leq \beta+\alpha \\ 1 & \lvert x \rvert \geq \beta+\alpha \end{cases}$	
4. Linear preference	$K(x) \begin{cases} \lvert x \rvert / \alpha & if\ \lvert x \rvert \leq \alpha \\ 1 & Otherwise \end{cases}$	
5. Gaussian	$K(x) = \begin{cases} 0 & if\ x = 0 \\ 1 - e^{-x^2/2\sigma^2} & if\ \lvert x \rvert > 0 \end{cases}$	
6. Linear preference and indifference area	$K(x) \begin{cases} 0 & \lvert x \rvert \leq \beta \\ (\lvert x \rvert - \beta)/\alpha & \beta < \lvert x \rvert \leq \beta+\alpha \\ 1 & Otherwise \end{cases}$	

Figure 2.6. List of generalized criteria for PROMETHEE method. Adapted from Bufardi et al. (2008)

In Fig. 2.6, β denotes a threshold of indifference and α denotes a threshold of strict preference. The preference threshold is the smallest sufficient deviation which considered sufficient to generate a full preference (Figueira et al., 2005). Indifference threshold is the largest acceptable deviation which is considered negligible by decision maker (Figueira et al., 2005). In Fig. 2.6, σ denotes an intermediate value between α and β (Figueira et al., 2005).

The sequential steps for the PROMETHEE I and II procedures are shown as Fig. 2.7; this sequence is according to Behzadian et al. (2010) and was augmented by the author of this thesis.

Step 1.Constructing the evaluation table (decision matrix)

↓

Step 2.Obtaining the required parameters from decision makers and selecting appropriate generalized criterion functions

↓

Step 3.Calculation of the deviations based on pair-wise comparisons

$$d_j(a,b) = g_j(a) - g_j(b)$$

↓

Step 4.Application of preference function

$$P_j(a,b) = F_j\left[d_j(a,b)\right] \qquad \text{j= 1,.....k}$$

↓

Step 5.Calculation of global preference index

$$\forall\, a,b \in A , \quad \pi(a,b) = \sum_{j=1}^{k} w_j \times P_j(a,b)$$

Where $\pi(a,b)$ and w_j denotes the global preference index and weight associated to criterion j, respectively. In addition $\sum_{j=1}^{k} w_j = 1$

↓

Step 6.Calculation of outranking flows/ partial ranking of PROMETHEE I

$$\phi^+(\mathrm{a}) = \frac{1}{n-1}\sum_{x \in A} \pi(a,x) \text{ and } \phi^-(\mathrm{a}) = \frac{1}{n-1}\sum_{x \in A} \pi(x,a)$$

Where $\phi^+(.)$ and $\phi^-(.)$ denotes the positive and negative outranking flow function for each alternative. *n* denotes the number of the alternatives.

↓

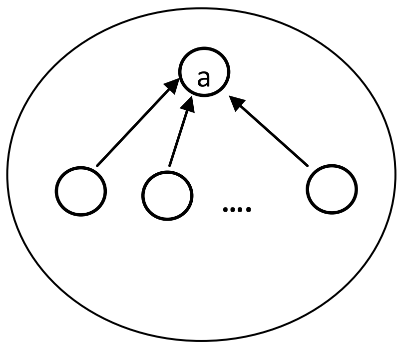
Step 7.Calculation of net outranking flow/ complete ranking of PROMETHEE II

$$\phi(\mathrm{a}) = \phi^+(\mathrm{a}) - \phi^-(\mathrm{a})$$

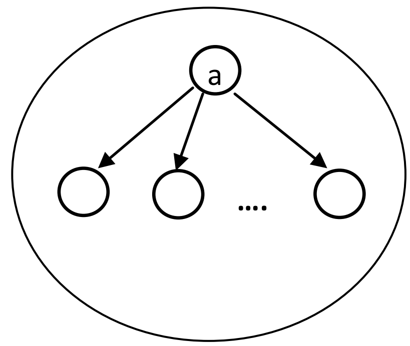
Where $\phi(\mathrm{a})$ denotes the net outranking flow for each alternative

Figure 2.7. Sequential steps of PROMETHEE I and II procedures

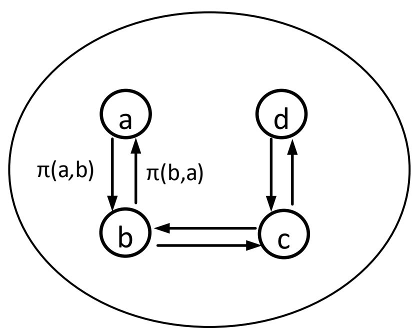
In order to measure the overall preference of an alternative 'a' over another alternative 'b', the global preference index, $\pi(\mathrm{a,b})$, was defined in PROMETHEE to point out the degree of preference of alternative 'a' over 'b' by considering their values for all criteria in the evaluation table (see Fig. 2.8 (C)). PROMETHEE also defines positive and negative outranking flows of an alternative which are shown by ϕ^+ and ϕ^-. ϕ^+ is called out-coming flow and ϕ^- is called in-coming outranking flow. The symbol $\phi^{-}(a)$ indicates the relative preference of an alternative like 'a' to the rest of the alternatives as shown in Fig.2.8(a). Additionally, $\phi^{+}(a)$ indicates the relative preference of the rest of the alternatives to alternative 'a' for a decision making problem as shown in Fig. 2.8(b). The three terms "global preference index", "in-coming outranking flow", and "out-coming outranking flow" are graphically presented in Fig.2.8.



a. In-coming outranking flow $\phi^{-}(a)$



b. Out-coming outranking flow $\phi^{+}(a)$



c. Global preference indices $\pi(a, b)$ and $\pi(b, a)$

Figure 2.8. Graphical representation of global preference index (c) and outranking flows (a and b) of PROMETHEE (adapted from Figueira et al. 2005)

If P stands for Preferences and I stands for Indifferences, then Fig. 2.9 summarizes how alternatives can be ranked by using PROMETHEE I and II based on Vincke and Brans (1985).

<table>
<tr><td rowspan="4">1</td><td rowspan="4"><u>Total Preorders</u>

(P^+, I^+) and (P^-, I^-)</td><td>a P^+ b iff $\phi^+(a) > \phi^+(b)$</td></tr>
<tr><td>a P^- b iff $\phi^-(a) < \phi^-(b)$</td></tr>
<tr><td>a I^+ b iff $\phi^+(a) = \phi^+(b)$</td></tr>
<tr><td>a I^- b iff $\phi^-(a) = \phi^-(b)$</td></tr>
<tr><td rowspan="4">2</td><td colspan="2"><u>Partial outranking</u> (PROMETHEE I) :</td></tr>
<tr><td>2.1. a outranks b</td><td>If a P^+ b and a P^- b
a P^+ b and a I^- b
a I^+ b and a P^- b</td></tr>
<tr><td>2.2. a is indifferent to b</td><td>if a I^+ b and a I^- b</td></tr>
<tr><td>2.3. a and b are incomparable</td><td>Otherwise</td></tr>
<tr><td>3</td><td colspan="2"><u>Complete Outranking</u> (PROMETHEE II) :
$\phi(a) = \phi^+(a) - \phi^-(a)$</td></tr>
</table>

Figure 2.9. Ultimate outranking indicators of PROMETHEE I and II

By applying the possible outcomes shown in Fig. 2.9, the alternatives of a decision-making problem can be ranked.

2.5.6. ELimination Et Choix Traduisant la REalité

Another classical type of MCDM is ELimination Et Choix Traduisant la REalité ELECTRE (translation: ELimination and Choice Expressing the REality), or ELECTRE (Benayoun, 1966; Roy, 1985). ELECTRE was developed by a research team at a European consultancy company called SEMA (Figueira et al., 2005). The first version of the ELECTRE family of methods is called ELECTRE I, which was developed by Roy (1968). ELECTRE I was the first outranking method, and several other methods were developed during the 1970s and 1980s (Hatami-Marbini and Tanava, 2011). Several versions of ELECTRE exist, such as ELECTRE I, ELECTRE IS, ELECTRE II, ELECTRE III, ELECTRE IV, ELECTRE TRI (Bojkovic et al., 2010; Roy, 1991).

Pairwise comparisons among alternatives in a decision making problem under each criterion is the basic concept of ELECTRE (Kahraman, 2008; Bojkovic et al., 2010). ELECTRE, like other MCDM methods, has some advantages and disadvantages. For instance, Hatami-Marbini and Tavana (2011) stated that the ELECTRE method has the capability of outranking methods to consider ordinal scales without the need to convert the original, as well as the ability to deal with imperfect knowledge by the utilization of indifference and preference thresholds. Roy (1991) identified other advantages of ELECTRE such as its provision of robustness analysis.

There are some differences among different versions of the ELECTRE family (similar to the PROMETHEE family); these differences can assist decision makers to select the solution that fits their circumstances in their decision-making problem. Research literature (Balaji et al., 2009; Buchanan et al., 2000; Marzouk, 2011) points out that ELECTRE methods differ operationally, and circumstances of the decision problem should be considered in the selection of one of them. For example, according to Bojkovic et al. (2010), ELECTRE I can deal with problems where the objective is to select only one alternative. Additionally, ELECTRE II, III, IV can be applied for ranking alternatives, and ELECTRE TRI can be also be applied for problems where the objective is to sort the alternatives (Bojkovic et al., 2010). Balaji et al. (2009) and Buchanan et al. (2000) also added that when the quantification of relative importance of criteria is desirable, ELECTRE III can be applied. On the other hand, ELECTRE IV can be used when this type of quantification is not possible. Roy (1991) discussed in more detail how a decision maker can select a method from the ELECTRE family by considering indicators including: the possibility for taking into account indifferences and/or preference thresholds, the number and nature of outranking relations, the necessity of the quantification of the relative importance of criteria, and the description of the potential final result.

In order to better understand what the ELECTRE method is and how it provides a decision making solution, the processes of ELECTRE III are described in the following section. The reason for presenting ELECTRE III in particular is that there is widespread application of this method in the research literature (in comparison with ELECTRE). For instance, Tam et al. (2003) and Karagiannidis and Moussiopoulos (1995) selected ELECTRE III by referring to the following statement that has been provided by Vincke (1992) about ELECTRE III:

> ''it involves some aspects that are often neglected by other methods and for yielding relatively stable results.''

2.5.7. ELimination Et Choix Traduisant la REalité III

ELECTRE III, like the other types of ELECTRE methods, utilizes pairwise comparisons among alternatives, providing a concordance index from each comparison; more detail of this process is provided in the remainder of this section. As noted earlier, ELECTRE III is capable of handling the uncertainties and imprecise information that exists in decision-making processes. Three thresholds are defined for each criterion in ELECTRE III: indifference (***q***), preference (***p***), and veto (***v***) thresholds (Roy, 1978).

Raju and Duckstein (2004) described each aforementioned threshold for some criterion ***j***:

> "$\boldsymbol{q_j}$ is the indifference threshold that represents the largest difference that is considered negligible by the decision maker when comparing two alternative strategies of that criterion,
>
> $\boldsymbol{p_j}$ is the preference threshold that represents the smallest difference that justifies a strict preference for one of the two alternative strategies and
>
> $\boldsymbol{v_j}$ is the veto threshold that represents a difference so large that it will prohibit an alternative strategy from outranking the other, even if the former is much better for the other criteria."

These three thresholds are in the order $\boldsymbol{v_j > p_j > q_j}$. For each pairwise comparison, a specific area between the value of that two alternatives can be constructed that is called the "zone of hesitation" or weak preference (Buchanan and Vanderpooten, 2007).

Suppose that 'a' and 'b' denote two alternatives, and their values with respect to criterion j are $g(a)$ and $g(b)$, respectively. By considering the aforementioned thresholds, three relations exist (Figueira et al., 2009; Buchanan and Vanderpooten, 2007; Raju and Duckstein, 2004) between alternative a and b as noted below:

1. $g(a) - g(b) > p \iff a\boldsymbol{P}b$ *(a is strictly preferred to b)* *Equation 2.8*
2. $q < g(a) - g(b) \leq p \iff a\boldsymbol{Q}b$ *(a is weakly preferred to b)* *Equation 2.9*
3. $|g(a) - g(b)| \leq q \iff a\boldsymbol{I}b$ *(a is indifference to b; and b to a)* *Equation 2.10*

As can be inferred from above relations, three zones—indifference, weak preference, and strict preference—can be identified; as depicted in Fig. 2.8.

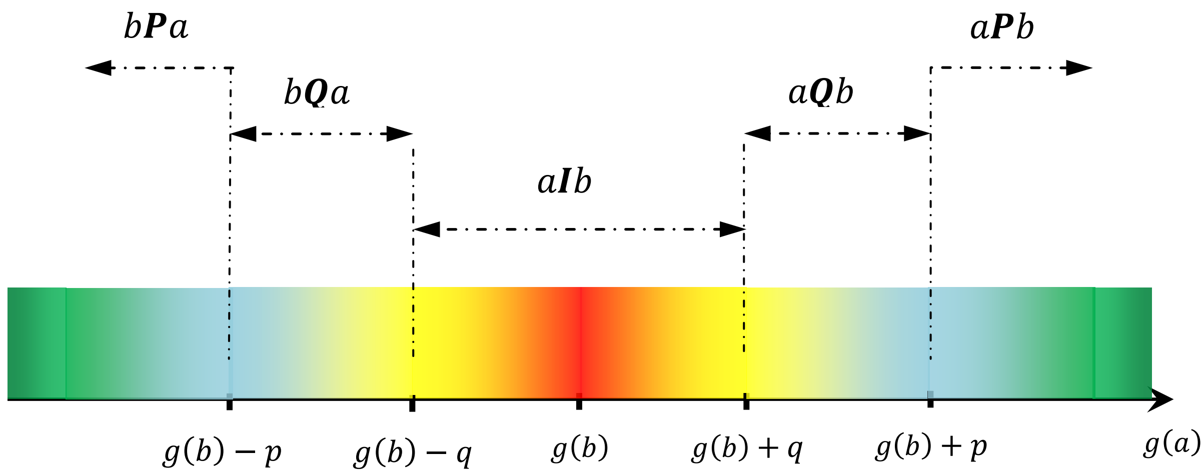


Figure 2.10. Schematic presentation of three types of zone; indifference (I), weak preference (Q), and strict preference (P)

In addition to the three zones, Fig. 2.8 schematically shows why it has been said that ELECTRE III is capable of dealing with fuzzy environments, and shows how uncertainty and imprecise concepts are being applied in an ELECTRE III context.

As the first step, pairwise comparisons between alternatives with respect to each decision criterion are carried out. Two indices—including concordance index and discordance index—are assigned to each comparison. For a comparison between two alternatives like *a* and *b* with respect to criterion *j,* a concordance index like $\mathrm{C_j(a,b)}$ is applied to quantify the relative dominance of alternative *a* over alternative *b* with respect to criterion *j.* The value of concordance indices varies from 0 to 1 and the overall dominance of an alternative over another for all decision criteria by considering the weight of each criterion, w_j, can be calculated as follows:

$$C(a,b)=\frac{1}{W}\sum_{j=1}^{n} w_j c_j(a,b) \qquad \textit{Equation 2.11}$$

Where *n* denotes the number of criteria, and

$$w=\sum_{j=1}^{n} w_j \qquad \textit{Equation 2.12}$$

Concordance and discordance indices can be better presented in a matrix format:

$$C=\begin{bmatrix} c_{1,1} & \cdots & c_{1,n} \\ \vdots & \ddots & \vdots \\ c_{n,1} & \cdots & c_{n,n} \end{bmatrix}, D=\begin{bmatrix} d_{1,1} & \cdots & d_{1,n} \\ \vdots & \ddots & \vdots \\ d_{n,1} & \cdots & d_{n,n} \end{bmatrix} \qquad \textit{Equation 2.13}$$

The value of concordance and discordance indices varies from 0 to 1:

$$
C_j(a,b) = \begin{cases} 1 & \text{if} \quad g_j(a) + q_j \geq g_j(b) \\ 0 & \text{if} \quad g_j(a) + p_j \leq g_j(b) \\ \frac{g_j(a) - g_j(b) + p_j}{p_j - q_j} & \text{Otherwise} \end{cases} \qquad \textit{Equation 2.14}
$$

and

$$
d_j(a,b) = \begin{cases} 0 & \text{if} \quad g_j(b) \leq g_j(a) + p_j(g_j(a)) \\ 1 & \text{if} \quad g_j(b) \geq g_j(a) + v_j(g_j(a)) \\ \frac{g_j(b) - g_j(a) - p_j}{v_j - p_j} & \text{Otherwise} \end{cases} \qquad \textit{Equation 2.15}
$$

In order to better understanding of how concordance and discordance indices can be valued, the two following curves are provided:

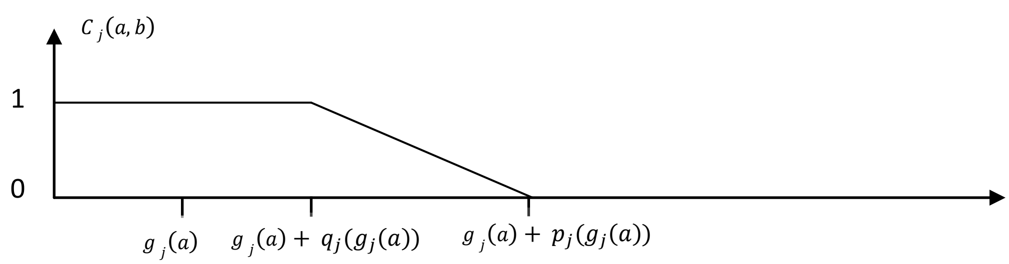


Figure 2.11. Concordance index of gi

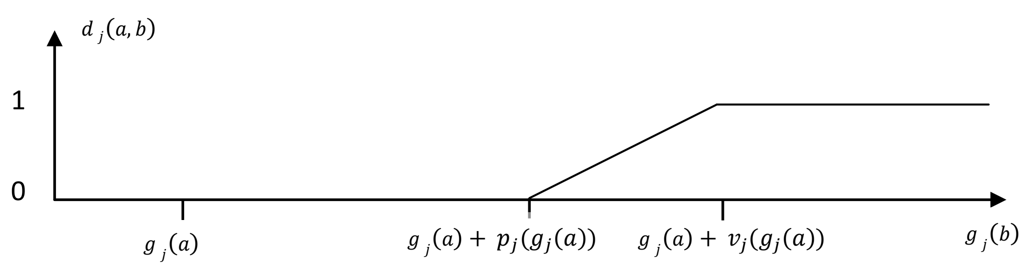


Figure 2.12. Discordance index of gi

2.5.8. Technique for Order Preference by Similarity to Ideal Solution

The last type of Multi Criteria Decision Making method described in this section is the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). This method was developed by Hwang and Yoon (1981) and is capable of ranking finite number of alternatives by considering simultaneously two indices of closeness: 1. shortest distance to positive ideal solution, and 2. farthest distance from negative ideal solution. According to Rao (2007), positive and negative ideal solutions are actually hypothetical solutions that are obtained when all values of alternatives in the decision matrix have their extreme values. In this regard, for a positive ideal solution, all values of alternatives have the maximum (best) values which are allowable for each criterion. In contrast, when all alternatives have their allowable minimum (worst) values, a negative ideal solution for that decision problem can be calculated.

Similar to other decision support methods, the research literature has supported this method and has utilized its capabilities in a wide range of topics (Cha and Jung, 2001; Chen, 2000; Deng et al., 2000; Shih et al., 2007; Chen and Tzeng, 2004; Lai et al., 1994; Abo-Sinna and Amer, 2005; Jahanshahloo et al., 2009; Chu, 2002).

The procedure of TOPSIS can be illustrated in a series of steps that can be classified into three main parts (Hatami-Marbini and Tavana, 2011): (1) constructing the decision matrix, (2) calculating the closeness coefficients, and (3) ranking the alternatives. The multiple steps of TOPSIS are summarized and depicted in Fig 2.12; more details of these steps can be found in Vahdani et al. (2011) and Rao et al. (2007).

***Step 1*:**

Identification and selection of significant important decision criteria as well as formulization of feasible and effective alternative

***Step 2*:**

Computation of relative importance (weight) of selected criteria and normalization of assigned weights of criteria as well as construction of decision matrix (or table)

***Step 3*:**

Standardization (normalization) of performance rate of decision matrix by utilization of a method of normalization like what has been mentioned as follows:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} {x^2}_{ij}}} \quad ,i = 1,2,\dots,m; \quad j = 1,2,\dots.,n,$$

Where r_{ij} denotes normalized the value of alternative i with respect to the criterion j.

***Step 4*:**

Re-construction of decision matrix but this time with weighted normalized performance rates.

$$V = (v_{ij})_{m\times n} \text{ where } v_{ij} = w_{ij} \times r_{ij} \quad , i = 1,2,\dots,m; \quad j = 1,2,\dots.,n,$$

v_{ij} denotes weighted normalized the value of alternative i with respect to the criterion j and V is weighted normalized decision matrix.

***Step 5*:**

Calculation of positive and negative ideal solutions.

$$S^+ = \{{v^+}_1,\dots,{v^+}_m\} = \{(max_j v_{ij} \mid j\in C_b), (min_j v_{ij} \mid j\in C_c)\},$$

$$S^- = \{{v^-}_1,\dots,{v^-}_m\} = \{(min_j v_{ij} \mid j\in C_b), (max_j v_{ij} \mid j\in C_c)\},$$

where C_b , C_c denote the set of criteria which their higher value and less value are desirable, respectively. S^+ and S^- are positive and negative ideal solution, respectively.

Figure 2.13. Stepwise procedure of TOPSIS method

***Step 6*:**

Calculation of Euclidean distance of each alternative from the positive and negative ideal solutions.

$$\rho^{+}{}_{i} = \sqrt{\sum_{j=1}^{n}(v_{ij} - v^{+}{}_{j})^{2}} \ , \ \rho^{-}{}_{i} = \sqrt{\sum_{j=1}^{n}(v_{ij} - v^{-}{}_{j})^{2}} , \ i = 1,2, \dots , m$$

Where, $\rho^{+}{}_{i}$ and $\rho^{-}{}_{i}$ denote distance of alternative i from positive ideal solution and negative ideal solution, respectively.

***Step 7*:**

Determination of relative closeness of each alternative to the ideal solution.

$$\lambda_i = \frac{\rho^{-}{}_{i}}{\rho^{+}{}_{i} + \rho^{-}{}_{i}} \ , \qquad i = 1, 2, \dots , m$$

Where, λ_i denotes the relative closeness of alternative i (A_i) to the ideal solution (S^+)

***Step 8*:**

Providing order ranking of alternatives by considering the value of relative closeness of each alternative to the ideal solution (λ_i). At that sense, alternatives with higher value of λ_i are more desirable compared to other existing alternatives.

Figure 2.14. Continued stepwise procedure of TOPSIS method

Recent research (Hatami-Marbini and Tavana, 2011; Roghani et al., 2010; Shih et al., 2007) has indicated the advantages of TOPSIS over other MADM methods, specifically in some cases identifying advantages of this decision aid method in group decision-making environments (Bottani and Rizzi, 2006). These researchers have mentioned the advantages of the TOPSIS method (Kim et al., 1997), summarized as follows:

e. TOPSIS has a scalar value with the capability of simultaneous consideration of both existing and feasible best and worst alternatives of decision problem;

f. As shown in the flowchart of Fig. 2.13 and 2.14, the procedure of TOPSIS is simple; the application of meaningful indices from this procedures can be easily understood and followed;

g. This method provides a sound logic which demonstrates the rationale of human choice;

h. As one of the most important features of TOPSIS, the efficiency of each alternative can be calculated. This efficiency is computed by measuring the closeness of each alternative to ideal and anti ideal points;

i. Cumbersome pairwise comparisons among alternatives of decision problem are not necessary for TOPSIS;

j. The abilities and advantages of TOPSIS turn it into an effective decision-aid tool in group decision making environment;

k. Due to its meaningful and illustrative indices, TOPSIS is a suitable method for dealing with uncertain and fuzzy decision making environments.

2.6. Fuzzy Multi-Criteria Decision Making (FMCDM)

2.6.1. Brief History of Fuzzy Set Theory

The term ''fuzzy'' is generally used to describe mathematical models when crisp (i.e., accurate) values of alternatives and attributes cannot be defined (Kahraman, 2008a) and unsharp boundaries exist; this is a basic concept of fuzzy sets and they can deal with these uncertain and ambiguous situations (Taha and Rostam, 2011). In other words, typically an element either fully belongs or does not belong to a crisp set, whereas it can partially belong to a fuzzy set (Ertuğrul and Güneş, 2007). More details and definitions of fuzzy sets, fuzzy set theory, fuzzy numbers, and their basic arithmetic operations are presented later in this section.

Fuzzy set theory formally was proposed by Zadeh (1965) as a modeling tool for complex systems; Bellman and Zadeh (1970) applied this concept to decision-making problems. Generally speaking, a fuzzy set can be defined as an interval with unsharp boundaries (Hong and Choi, 2000) (explained in greater detail in the following sections). Since its origin, a significant amount of research has focused on different aspects of fuzzy set theory to develop this method and to extend its applications (Zimmermann, 1978; Zadeh, 1999; Roubens, 1978; Hannan, 1983; Chanas et al., 1984; Foody, 1992; Hsu and Chen, 1996).

Since the 1970s, the capabilities of fuzzy sets and fuzzy numbers have grabbed the attention of researchers; this section explains the method and its application to decision making. A short description of the most important research literature that made significant initial advances in the application of fuzzy sets and numbers in MCDM methods is provided.

As one of the first application of fuzzy sets in MCDM, Baas and Kwakernaak (1977) used fuzzy set theory to deal with inherent uncertainties that exist in the assessment of ratings and weights of a multi-criteria decision-making problem. According to Kahraman (2008), this approach was frequently used as the benchmark for similar decision models.

Saaty (1978) proposed a hierarchical structure for multiple-objective decision making in order to measure the relative fuzziness; this was accomplished by calculating the degree of membership of elements that derives from computing an eigenvector. Buckley (1985) also worked on Saaty's method (1978) and presented an evolutionary algorithm for calculating the fuzzy weights that is less complicated compared to what was earlier proposed by Saaty (1978). In 1980, Saaty proposed a pairwise comparison method that can consider human judgments in an MCDM process, which was extended later by other researchers such as De Graan (1980) and Lootsma (1985).

Van Laarhoven and Pedrycz (1983) worked on the pairwise comparison method developed by Saaty (1980) and they proposed to calculate the fuzzy weight for criteria and alternatives separately and, by doing so, the fuzzy score for alternatives as well as their sensitivity can be obtained. Van Laarhoven and Pedrycz's method also was modified by Boender, De Green, and Lootsma (1985), who used the minimization of a logarithmic regression function for calculating the weights of decision criteria. In 1982, Carlsson (1982) provided a conceptual framework that linked the concept of fuzzy with linear and goal programming in order to tackle MCDM problems.

2.6.2. Preliminaries

In order to gain a better understanding of what fuzzy sets and numbers are, three subsections are presented here. They include the detailed definition of fuzzy sets and numbers, membership functions, and some essential arithmetic operations for fuzzy numbers.

2.6.3. Fuzzy Sets and Fuzzy Numbers

This section presents mathematical definitions and notations of fuzzy set (Jahanshahloo et al., 2009; Yong, 2006; Bashiri and Hosseinzadeh, 2009).

As mentioned before, fuzzy sets generally correspond to sets with unsharp boundaries (Hong and Choi, 2000) while crisp sets correspond to sets with sharp boundaries. For a better understanding of what a fuzzy set is and what the differences are between fuzzy sets and crisp sets, a fuzzy set and a crisp set are presented simultaneously in Fig. 2.13.

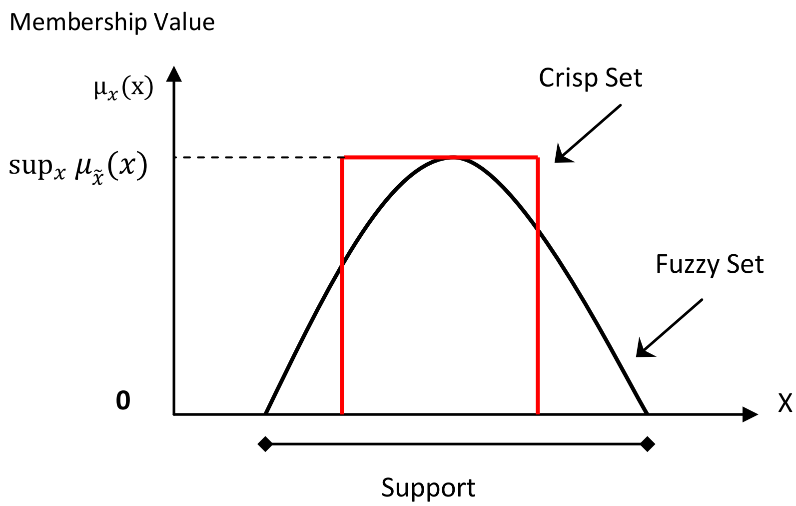


Figure 2.15. Schematic presentation of fuzzy set and crisp set

Let X be an universal set where its generic elements are denoted by x. For a crisp subset of X that can be denoted by A, the characteristic function μ_A from X to {0, 1} can be viewed as membership in A such that:

$$\mu_A(x) = \begin{cases} 1 & \text{if and only if } x \in A, \\ 0 & \text{Otherwise,} \end{cases}$$ *Equation 2.18*

Where, {0, 1} is called the valuation set. In the case here the valuation set is allowed to be a real interval like [0, 1], A is called a fuzzy set (commonly denoted by $\tilde{A}$), in which case $\mu_{\tilde{A}}$ is the degree of membership of x in $\tilde{A}$ that is commonly called the membership function. In other words, in a fuzzy set, the membership function associates a real number in [0, 1] to each element of $x \in X$.

A set of ordered pairs as provided below can completely characterize a fuzzy set of $\tilde{A}$.

$$\tilde{A} = \{(x, \mu_{\tilde{A}})|\, x \in X\}$$ *Equation 2.19*

A fuzzy number can be defined as the real line $\mathbb{R}$ of a fuzzy set $\tilde{A}$ with a continuous membership and the requirement to be convex and normal as well. The terms ''convexity'' and ''normality'' in fuzzy theory are explained in following definitions.

A fuzzy set $\tilde{A}$ is normal if and only if:

$$sup_x \, \mu_{\tilde{x}}(x) = 1$$ *Equation 2.20*

According to Chen et al. (2004), a fuzzy set $\tilde{A}$ in X is convex if and only if

$$\mu \,(\lambda x + (1-\lambda)y) \geq min\{\mu(x), \mu\,(y)\}$$ *Equation 2.21*

For all $x, y \,\epsilon\, supp(\mu) = \{t \,\epsilon\, R^n: \mu(t) > 0\}, \lambda \in [0, 1]$. Chen et al. (2004) stated that by considering the aforementioned definition of convexity, the local maximizer is not necessarily a global maximizer in the case of maximizing a fuzzy decision. Jahanshahloo et al. (2009) also added that a fuzzy set is convex if all *α-level* sets are convex.

2.6.4. Membership Functions

As noted earlier, a membership function is defined for each fuzzy set to illustrate the degree of membership of elements to the fuzzy set, which can be viewed as the key idea of fuzzy set theory (Zadeh, 1999). This section shows different popular types of membership functions and how they can be mathematically formulated. This is followed by the definitions of some of the characteristics of fuzzy numbers.

Membership functions are generally named according to the shape of their curves; the most popular types of membership function for a fuzzy set are triangular, trapezoidal, Gaussian, and sigmodial. There are other types of membership function that Ertugrul and Güneş (2007) have identified, and all of this variety of functions can play a role in reducing the ambiguity in decision making. Due to the predominant application of two forms—triangular and trapezoidal membership functions—the mathematical formulation of these two forms are provided below and the schematic presentation of their membership functions are depicted in Fig.2.14 and Fig.2.15.

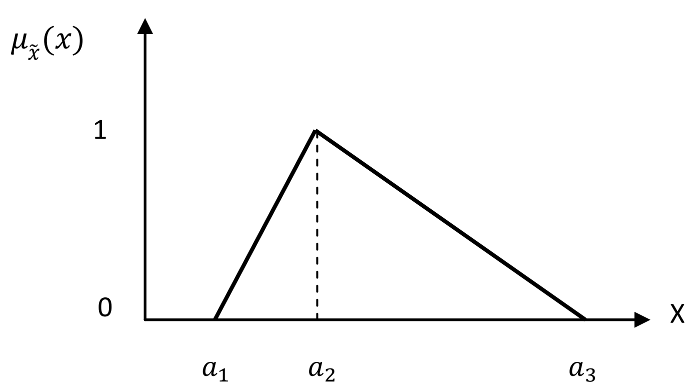


Figure 2.16. Triangular membership function

The mathematical formulation of the triangular membership function is shown in Fig.2.14 and is presented as follows.

$$\mu_{\tilde{x}}(x) = \begin{cases} 0 & x \leq a_1, \\ \dfrac{x - a_1}{a_2 - a_1} & a_1 \leq x \leq a_2, \\ \dfrac{x - a_3}{a_2 - a_3} & a_2 \leq x \leq a_3, \\ 0 & a_3 \leq x. \end{cases}$$

Equation 2.22

An example of a membership function with a trapezoidal shape is depicted in Fig. 2.15.

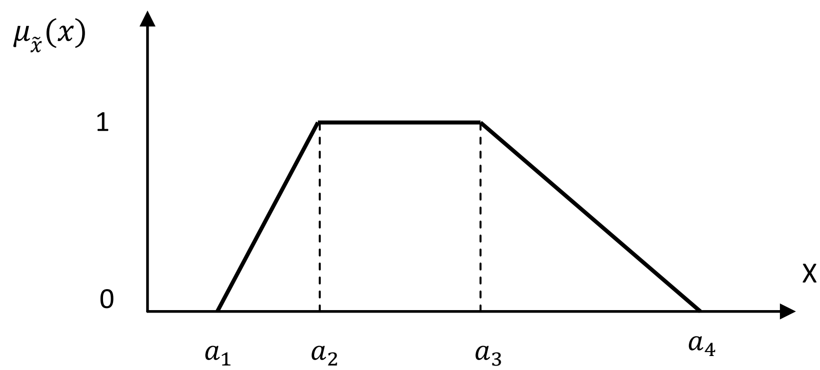


Figure 2.17. Trapezoidal membership function

The mathematical formulation of the trapezoidal membership function as shown in Fig. 2.15 is presented as follows:

$$\mu_{\tilde{x}}(x) = \begin{cases} 0 & x \le a_1, \\ \frac{x-a_1}{a_2-a_1} & a_1 \le x \le a_2, \\ 1 & a_2 \le x \le a_3, \\ \frac{x-a_4}{a_3-a_4} & a_3 \le x \le a_4, \\ 0 & a_4 \le x. \end{cases}$$

Equation 2.23

An important question in formulating or solving a problem in the fuzzy environment arises: what type of membership function is appropriate for the existing problem. El-Wahed (2008) stated that the experience of decision makers may be viewed as the key point in selecting a membership function. He also mentioned that different membership function may lead to different solutions for a specific problem. So, selecting a membership function is a subjective process that mainly depends on the preference of an individual assessor or a group of assessors (Singpurwalla et al., 2004). The importance of the fuzziness variable in formulating a decision-making problem like FMCDM can affect the selection of a membership function (El-Wahed et al., 2008). Besides the direct selection of membership function by decision makers or assessors, as El-Wahed et al. (2008) also mentioned, there are mathematical and statistical methods that can help to approximate or construct a proper membership function. In this regard, extensive research efforts have worked on estimating a membership function by application of artificial intelligence techniques such as genetic algorithms (Esmin and Lambert-Torres, 2007; Arslan and Kaya, 2001; Homaifar and McCormick, 1995; Herman et al., 2009), artificial neural networks (Ostermark, 1999), and ant colony algorithms (Jiang and Deng, 2008).

Some features of fuzzy numbers and operations on fuzzy sets, which are rooted in, or can be better defined by, their membership functions, are described in the following definitions:

The α-level set or α-cut of a fuzzy set $\tilde{A}$ is a crisp subset of X that is denoted by $[\tilde{A}]_\alpha$ such that:

$$[\tilde{A}]_\alpha = \{x \mid \mu_{\tilde{A}} \ge \alpha\}$$

Equation 2.24

Where, α ∈ [0, 1]. The lower and upper points of a fuzzy set α-cut are denoted by $[\tilde{A}]_\alpha^L$ and $[\tilde{A}]_\alpha^U$, respectively. An example of an α-cut of fuzzy set $\tilde{A}$ is provided in Fig.2.16.

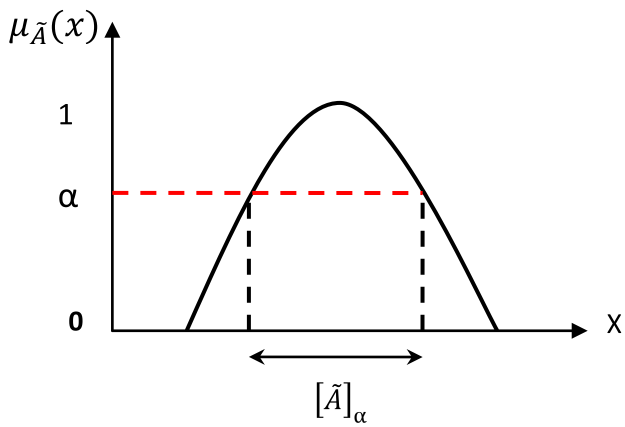


Figure 2.18. α-cut of fuzzy set A͂

If the membership value of a fuzzy number for all *x<0* equals zero, then that fuzzy number can be called a positive fuzzy number.

The distance between two fuzzy numbers $\tilde{A}$ and $\tilde{B}$ with triangular membership function obtained by using the vertex method is displayed as follows (Jahanshahloo et al., 2011):

$$d(\tilde{A}, \tilde{B}) = \sqrt{\frac{1}{3}[(a_1 - b_1)^2 + ((a_1 - b_1) - (a_2 - b_2))^2 + ((a_1 - b_1) + (a_3 - b_3)^2]} \quad \textit{Equ. 2.25}$$

According to Chen, C.T., (2000), the distance between two fuzzy numbers with triangular fuzzy membership function can be also calculated as follows:

$$d(\tilde{A}, \tilde{B}) = \sqrt{\frac{1}{3}[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2]} \qquad \textit{Equation 2.26}$$

In the case where two fuzzy numbers $\tilde{A}$ and $\tilde{B}$ have a trapezoidal membership function, the distance between these two fuzzy number is defined as follows (Ertuğrul and Güneş, 2007):

$$d(\tilde{A}, \tilde{B}) = \sqrt{\frac{1}{6}[(a_1 - b_1)^2 + 2(a_2 - b_2)^2 + 2(a_3 - b_3)^2 + (a_4 - b_4)]} \qquad \textit{Equation 2.27}$$

Unions and intersection of two fuzzy sets $\tilde{A}$ and $\tilde{B}$, which are usually denoted by "∪"and "∩", respectively, can be better defined with the help of membership contexts which are as follows:

$$\mu_{\tilde{A} \cup \tilde{B}}(x) = max\, [\, \mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)] \qquad \forall x \in X, \qquad \textit{Equation 2.28}$$

$$\mu_{\tilde{A}\cap\tilde{B}}(x) = min\,[\,\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)] \qquad \forall x \in X. \qquad \textit{Equation 2.29}$$

For better understanding of the intersection and unions operations between fuzzy sets, two examples of these two interval operations are illustrated in Fig.2.17.

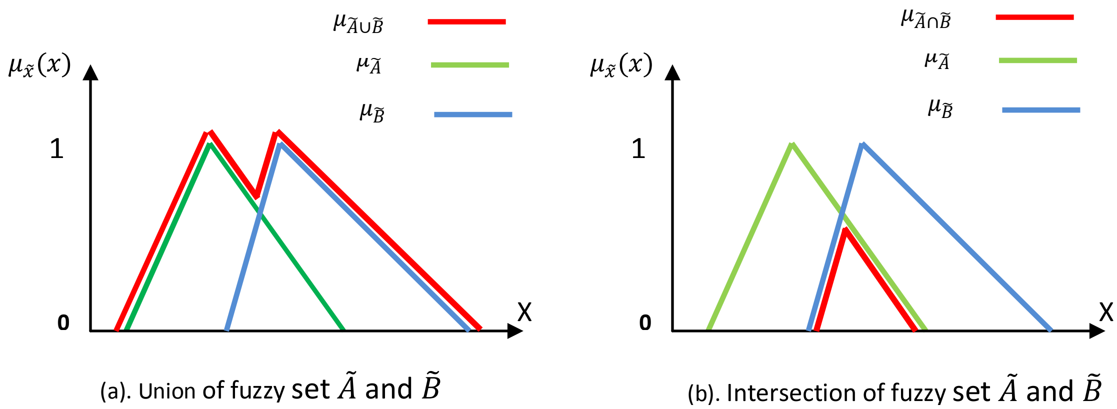


Figure 2.19. Schematic representation of intersection (a) and union (b) Operation of fuzzy set A˜ and B˜

The condition of equality between two fuzzy sets $\tilde{A}$ and $\tilde{B}$ (Singpurwalla and Booker, 2004) assessed by considering their membership functions are as follows:

$$If \quad \mu_{\tilde{A}}(x) = \mu_{\tilde{B}}(x) \qquad \forall x \in X \quad then \;\; \tilde{A} = \tilde{B} \;\; (and\ vice\ versa). \qquad \textit{Equation 2.30}$$

2.6.5. Fuzzy Arithmetic Operations

Operations between fuzzy numbers and also between fuzzy numbers and real numbers are always part of solving a problem, this also includes fuzzy variables. Some of the main algebraic fuzzy number operations are described in this section. Let $\tilde{A}$ and $\tilde{B}$ be positive fuzzy numbers with triangular membership function, $\tilde{A} = (a_1, a_2, a_3)$ and $\tilde{B}$ =(b_1, b_2, b_3), and let r be a positive real number, $r = (r, r, r)$, then the main operations can be defined as follows:

$$\tilde{A} \oplus \tilde{B} = (a_1 + b_1, a_2 + b_2, a_3 + b_3), \qquad \textit{Equation 2.31}$$

$$\tilde{A} \ominus \tilde{B} = (a_1 - b_1, a_2 - b_2, a_3 - b_3), \qquad \textit{Equation 2.32}$$

$$\tilde{A} \otimes \tilde{B} \cong (a_1 b_1, a_2 b_2, a_3 b_3), \qquad \textit{Equation 2.33}$$

$$\tilde{A} \otimes r = (a_1 r, a_2 r, a_3 r). \qquad \textit{Equation 2.34}$$

Where ⊕, ⊖, and ⊗ denote fuzzy sum, fuzzy subtraction, fuzzy multiplication, respectively. Fuzzy operations between fuzzy numbers with other types of membership function are the same aforementioned trends as long as they have the same type of membership functions. It should be noted that the multiplication of two fuzzy numbers is only an approximate triangular fuzzy number (Vahdani et al., 2011).

According to Taha and Rostam et al. (2011), the division of two positive fuzzy numbers $\tilde{A}$ and $\tilde{B}$, as well as the inversion of a fuzzy number, can be defined below:

$$\tilde{A}\,/\tilde{B} = (a_1/b_3, a_2/b_2, a_3/b_1) \qquad \textit{Equation 2.35}$$

$$(\tilde{A})^{-1} = (1/a_3\,, 1/a_2\,, 1/a_1\,) \qquad \textit{Equation 2.36}$$

2.7. Application of Fuzzy Theory in Multi-Criteria Decision Making

The application of fuzzy set theory in MCDM is presented in this section. After reviewing the definition and concept of fuzzy set theory, as well as its main arithmetic operations, during the previous section, it can now be shown why it has been selected and how fuzzy sets can be used.

2.7.1. Why Fuzzy Theory in Multi-Criteria Decision Making

Due to the complicated characteristics of real world decision-making problems (and more specifically, infrastructure management), the concepts and the capabilities of fuzzy theories can be used and considered during the problem formulation and problem solution phases to reduce uncertainties and ambiguities in the decision-making process. As noted earlier, the main goal of this research is to formulize a method in order to assist decision makers in investment planning for municipal infrastructure projects and, to this point, MCDM methods have been chosen as a decision-making aid and evaluation technique.

Now this important question can be answered in more detail: why MCMD tools need to use fuzzy variables and fuzzy logic as input data and rules. Considerable research has already provided some answers to the aforementioned question and has justified the application and importance of fuzzy theory in MCMD (Saaty, 1978; Baas and Kwakernaak, 1977; Chen et al., 2011; Boroushaki and Malczewski, 2010; Taha and Rostam, 2011). The author of this thesis believes that almost all of the aforementioned research efforts indirectly indicated the inabilities of crisp-values-based modeling and tools for dealing with imprecise information that is common in decision-making processes.

Real life problems take place in environments that consist of vague preferences, uncertain information and knowledge, and conflicting systems of logic (Figueira et al., 2005). When attempting to formulate a problem in this type of ambiguous situation, there is a high possibility for imprecise goals, constraints, and alternative consequence to emerge (Bellman and Zadeh, 1970). Chen and Klein (1997), building upon Chen et al. (1992), more specifically mentioned the main sources of this type of imprecise data and variables in a decision-making aid like MCDM as follows:

a. incomplete information,

b. non-obtainable information,

c. partial ignorance, and

d. unquantifiable information.

Thus, decision makers are faced with this complex situation in which there are several source of uncertainties in real-world decision-making problems, and there are inabilities of crisp values to reflect the characteristics of the problem appropriately. Moreover, this situation is made worse since fundamentally precise input data are required to effectively take advantages of decision-making aid tools like MCDM (Chen et al., 1992). All of these aforementioned situations and discussion direct attention to the application of a system or concept with the capabilities of dealing with different ambiguous aspects of decision problems reasonably and of providing input data and variables for decision makers and assessors. Accordingly, the features of fuzzy theory as noted earlier are well suited to the situation and the requirements that have been explained above, and the concepts of fuzzy theory can be applied to the decision-making method described in this research.

Figueira et al. (2005) indicated the importance of the applications of fuzzy set theory in MCDM. Since the first application and development of fuzzy MCDM, as noted during the previous sections, there has been considerable support for the effectiveness of fuzzy theory in the formulation of uncertain problems and extended research in this area (Carlsson, 1982; Buckley 1985; Hsu and Chen 1994; Herrera and Verdegay, 1997; Chen 2000; Karsak and Tolga, 2001; Jahanshahloo et al., 2011; Chen and Wang, 2011).

A summary of the most important parts of the discussion that has been presented above is provided in Fig.2.18, which emphasizes the reasons for selecting fuzzy theory as a solution for dealing with uncertain problems.

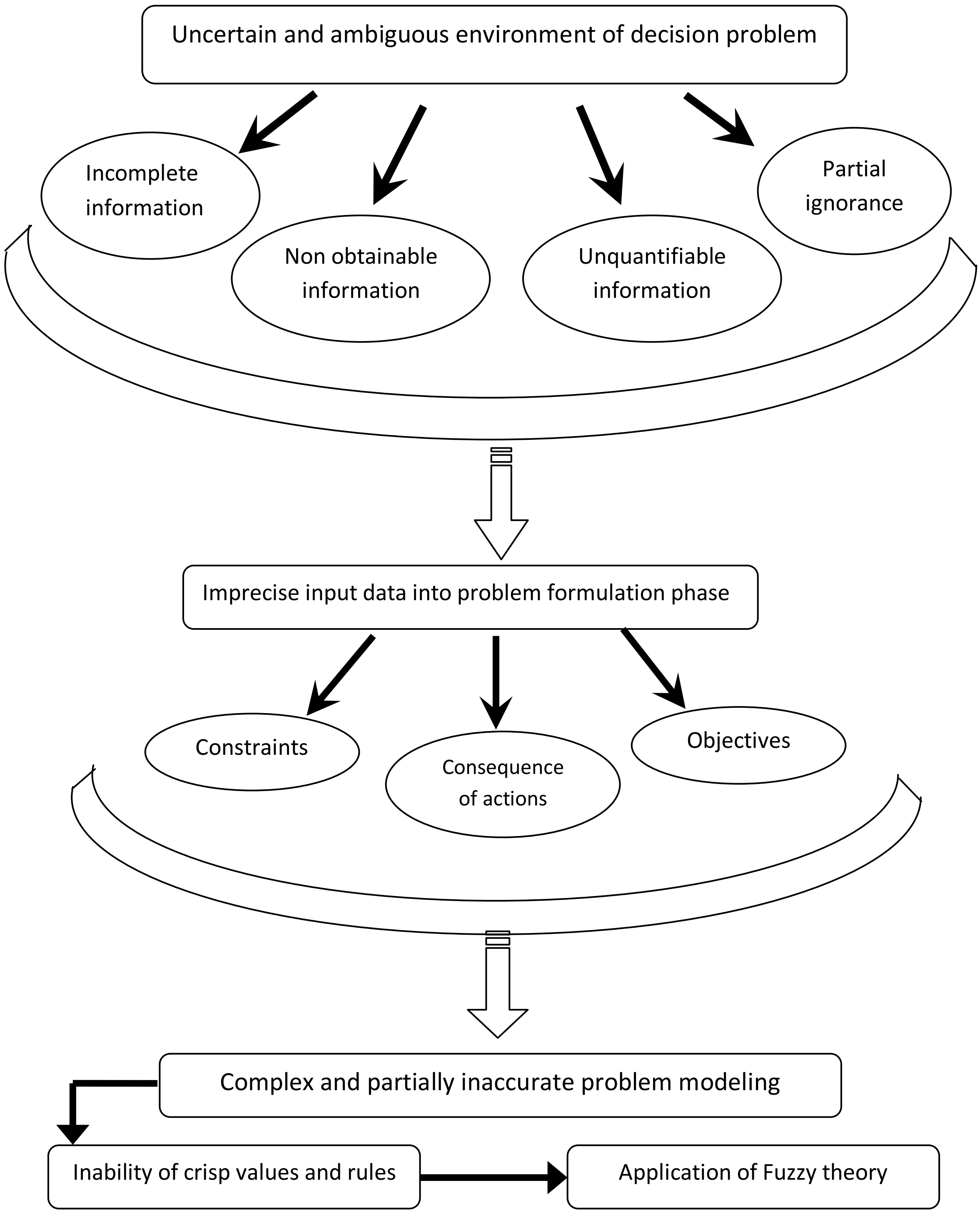


Figure 2.3. Uncertain environment of real world decision and necessity of adoption and application of fuzzy theory

Although it has been proven that fuzzy set theory can aid decision problem formulation to a large extent, as Kahraman (2008) and Chen et al. (1992) also pointed out, the manipulations and operations of fuzzy values are more difficult than crisp data and they commonly increase the amount of computations. So, by considering this matter on one hand, and the applicability and advantages of fuzzy theory on the other hand, this question arises: how and when should fuzzy set theory be taken into account as a technique in the decision-making process. Zimmermann (1978) provided a partial answer to this question when he postulated that the application of fuzzy set theory in MADM methods can be justified when the inability of crisp values for achieving the goals is proven. However, this topic still received the attention of researchers and remains a challenging issues in the MCDM arena (Yeh et al., 2000).

2.7.2. Source of Uncertainty in Multi-Criteria Decision Making

As noted earlier, decision makers and analysts are usually faced with situations where they cannot estimate or extract information in the fashion they desire. This situation can be viewed as the basis for vague and uncertain decisions. Chen et al. (2011a) defined uncertainty as a situation in which ''outcomes occur with probabilities that cannot be estimated''. The research literature has different interpretations and definitions of uncertainty that all indicate one common definition: the inability to make decisions with higher or reasonable confidence. Refsgaard et al. (2007) provided a comprehensive definition and view of uncertainty that is presented as follows:

> ''Uncertainty and associated terms such as error, risk and ignorance are defined and interpreted differently by different authors. The different definitions reflect the underlying scientific philosophical way of thinking and therefore typically vary among different scientific disciplines. In addition they vary depending on their purpose. ''

The uncertainty can actually be related more to the input data and models; input data includes the data selection and measurement. In addition, the term ''model'' consists of model structure and parameters (Chen et al., 2011a; Refsgaard et al., 2006). It is no surprise that in MCDMs, the weights of criteria and performance rates (attribute values) have been viewed as the greatest source of uncertainty. Some recent literature is listed in table 2.3 that shows how the various methods address the probable uncertainty and vagueness of MCDMs. There are three major techniques: probabilistic, fuzzy logic, and indicator-based methods (Chen et al., 2011a; Hajkowicz and Collins, 2007). They can all be used for the systematic treatment of the uncertainties that may exist in decision making. The indicator-based method is applied in problems without prior knowledge. The probabilistic method can be divided into two methods: analytical and numerical methods, which are suitable for simple and complex problem, respectively (Chen et al., 2011a).

Table 2.3. Some recent literature that applies MCDM to deal with uncertainty

Literature	Type of MCDM	Method for treatment of uncertainty	Source of uncertainty
Bottani and Rizzi (2006)	TOPSIS	Fuzzy set theory	Criterion Weights and attribute values
Kaya and Kahraman (2011)	AHP–ELECTRE	Fuzzy set theory	Criterion Weights and attribute values
		Sensitivity Analysis	Criterion Weights
Li and Zou (2011)	AHP	Fuzzy set theory	Criterion Weights
Chang and Yeh (2001)	SAW, TOPSIS, WP	Sensitivity Analysis	Type of MCDM
Aloini and Dulmin (2009)	PROMETHEE	Fuzzy set theory	input variables and the Alternative Ranking
Zavadskas et al. (2007)	Simple Additive Weight (SAW)	Sensitivity Analysis	Criterion Weights
Chen et al. (2009a)	AHP	Sensitivity Analysis	Criterion Weights
Dağdeviren (2008)	AHP-PROMETHEE	Sensitivity Analysis	Criterion Weights and attribute values

In addition, besides the three aforementioned methods, sensitive analysis has also been identified as a valuable tool that can be applied to deal with the probable subjectivity and imprecision (Hyde et al., 2004; Chatzimouratidis and Pilavachi, 2008). As a matter of fact, the mechanism of sensitivity analysis is in the opposite direction of uncertain analysis. It can investigate which part of the model has the most influence on outcomes as well as whether the results of the model can be significantly changed due to variations of inputs or not. Saltelli et al. (2000) presented a comprehensive definition of sensitivity analysis, which is ''the study of how the variation in the output of a model (numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources of variation, and how the model depends upon the information fed into it''. However, due to the extensive application of sensitive analysis, the author of this thesis believes that there is a possibility that someone may mistakenly use sensitivity analysis instead of uncertainty analysis. For instance, Beynon et al. (2008) applied the term ''sensitivity analysis'' as ''uncertainty analysis'', while in fact, as it noted previously, sensitive analysis is fundamentally different from uncertainty analysis. So, discrimination fundamentally exists between sensitivity analysis and three methods including fuzzy logic, probabilistic, and indicator-based method.

Chapter 3 Methodology

3.1. Introduction

The first chapter described the main objective and overall methodology of this research. The second chapter provided a summary of the literature review that mainly focused on decision-making methods and the inherent uncertainty that is part of any decision making. Now, this third chapter describes the three main parts of the decision making procedure in detail. These three main parts are: decision criteria selection, decision criteria weight, and alternative evaluation. Additionally, two stepwise procedures are provided in sections 3.3 and 3.4. to provide a better understanding of what procedures are and how they should be followed.

3.2. Decision Criteria

In this chapter, based on a series of research group discussions and extensive review of literature in the field, (Pantelias, 2005), an initial set of significant decision criteria have been identified and classified in order to evaluate municipal infrastructure projects. These are presented in Table 3.1. The identification of these criteria for evaluating infrastructure projects was done by reviewing previous research efforts from a wide range of decision making, as well as by seeking and applying expert knowledge from the infrastructure management community to revise input, to add more information and to eliminate insignificant criteria. To better understand what the significant criteria are and how they impact the evaluation of a project, these decision criteria are categorized into five main groups: (i) Technical and Engineering Parameters, (ii) Economic Parameters, (iii) Financial Parameters, (iv) Environmental Parameters, and (v) Social Parameters. These decision criteria are presented in Table 3.1, are discussed in the following chapter, and are based on an on-line questionnaire provided to a selection of Canadian municipalities in an effort to evaluate current best practices in the industry.

Table 3.1. Decision criteria and the category of decision criteria

1. Technical/ Engineering Parameters	**2. Economic Parameters**	**3. Financial Parameters**	**4.Environmental Parameters**	**5. Social Parameters**
1.1 Asset Condition 1.2 Remaining service life 1.3 Asset Age 1.4 Level of service 1.5 Deterioration Rate 1.6 Maintainability 1.7 Risk of failure 1.8 Constructability	2.1 Project cost 2.2 Indirect cost 2.3 Agency Cost/ Benefit 2.4 Social Cost/ Benefit 2.5 User Cost/ Benefit	3.1 Available Budget 3.2 Life Cycle Cost 3.3 Financial Risk 3.4 Asset Value	4.1 Effect during normal operation 4.2 Effect due to failure 4.3 Effect during construction	5.1 User's Opinion/ Complaints/ feedback 5.2 Public demands (usage) 5.3 Proximity of project major urban areas 5.4 Geographical distribution of funds 5.5 Safety 5.6 Effect during Operation

3.3. Weights of Decision Criteria

The individual decision criteria and the categories of decision criteria identified in Table 3.1 do not always have the same impact on the decision making and evaluation of projects. Furthermore, the differences between the relative importance of individual criterion can vary from one decision maker to another. In summary, a method is needed that should consider: (i) the opinions of different decision makers for a specific project and (ii) the relative importance of individual criteria or categories of criteria (commonly called weights of criteria). It has been determined in this research that the Analytical Hierarchy Process (AHP) can be used to assign the weights to selected decision criteria (Kaya and Kahraman, 2011; Charilas et al., 2009; Taha and Rostam, 2011).

As discussed earlier, fuzzy numbers have been identified as an effective way to deal with uncertainties in decision making. Accordingly, linguistic fuzzy numbers were chosen to deal with the uncertainties that may exist in assigning the weights to the decision criteria (Fu, 2008; Doukas, et al.

2007; Tavana and Hatami-Marbini, 2011). As listed in Table.3.2 and discussed in Chapter 2, these fuzzy numbers are always positive and have triangular membership functions.

Table 3.2. Linguistic variables for the importance weight of each criterion

Very Low (VL)	(0, 0, 0.3)
Low (L)	(0, 0.3, 0.5)
Medium (M)	(0.3, 0.5, 0.7)
High (H)	(0.7, 0.9, 1)
Very High (VH)	(0.7, 1, 1)

A review of AHP, a type of Multi Criteria Decision Making (MCDM), was provided in Chapter 2. AHP, by applying a strong hierarchy structure as described earlier, attempts to simplify complex and ill-structure problems. With respect to the five main categories of decision criteria in this research, AHP is ideally suited to the situation of this type of decision-making problem. The following sections present two approaches to calculate the weight of decision criteria. The concepts of the AHP method have been applied in both approaches.

3.3.1. Pair-wise Approach

The first approach is based on pairwise comparisons of decision criteria. Due to inconsistency that may appear in the pairwise comparisons, the author of this thesis believes that this approach may lose its effectiveness when the number of decision criteria is greater than six or seven. In this pair-wise approach, it has been assumed for pragmatic reasons and for simplicity of calculations that the ratings from each decision maker from the individual municipalities are equally important; then by using an arithmetic mean operation, the average rate for each decision criteria can be readily calculated.

An arithmetic mean operation for calculating fuzzy variables under a group decision making situation is shown in Equation 3.1.

$$\tilde{x}_{ij} = \frac{1}{N}[\tilde{x}_{ij}{}^{1} \oplus \tilde{x}_{ij}{}^{2} \oplus \ \dots \ \oplus \tilde{x}_{ij}{}^{n}] \qquad \textit{Equation 3.1}$$

Where *N* denotes the number of decision makers and $\tilde{x}_{ij}{}^{n}$ represents a fuzzy variable that denotes the evaluation of the n^{th} decision maker on the pairwise importance comparison of the i^{th} and j^{th} criteria.

Now, after using the arithmetic mean operation and considering the opinions of all decision makers, a comparison matrix of criteria weights can be constructed as follows.

$$X = \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{1m} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \cdots & \tilde{x}_{mm} \end{bmatrix} \qquad \textit{Equation 3.2}$$

Where

$$\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}) \qquad \textit{Equation 3.3}$$

As discussed in section 2.6.3, the three parameters a_{ij}, b_{ij}, c_{ij} are the three elements of a fuzzy number which has a triangular membership function.

The use of five main categories of decision criteria in this research requires six comparison matrices. One matrix is required for the evaluation of the relative importance of the main categories, and then one matrix is required for each category to evaluate the relative importance of the sub-criteria.

By constructing the comparison matrix, the fuzzy weight can be obtained through the following procedures from step 1 to 8, as shown in Fig. 3.1.

As the first step, the geometric mean operation is applied on each row in order to obtain a unique fuzzy number for each decision criteria. This geometric mean operation is given as:

$$a_i = [\prod_{k=1}^{m} a_{ik}]^{\frac{1}{m}} \qquad \textit{Equation 3.4}$$

And then by summation of obtained values, *a* will be as follows:

$$a = \sum_{i=1}^{m} a_i \qquad \textit{Equation 3.5}$$

Similarly, by application of the two previous equations, *b* and *c* can be calculated. Finally, the normalized fuzzy weight of each criterion is given by the following mathematical equation:

$$\widetilde{W}_i = \left(\frac{a_i}{c}, \frac{b_i}{b}, \frac{c_i}{a}\right), \quad \forall i \qquad \textit{Equation 3.6}$$

These normalized fuzzy weights of decision criteria can be defuzzified using following equation:

$$w'_i = \left(\frac{\frac{a_i}{c} + 2\left(\frac{b_i}{b}\right) + \frac{c_i}{a}}{4}\right) \qquad \textit{Equation 3.7}$$

Finally, the following equation is used in order to normalize the defuzzified (i.e., crisp) weights:

$$W_i = \frac{w'_i}{\sum_{i=1}^{m} w'_i}, i = 1, 2, \ldots, m \qquad \textit{Equation 3.8}$$

All of the steps required for calculating the weight of the evaluation criteria are schematically summarized in Fig. 3.1.

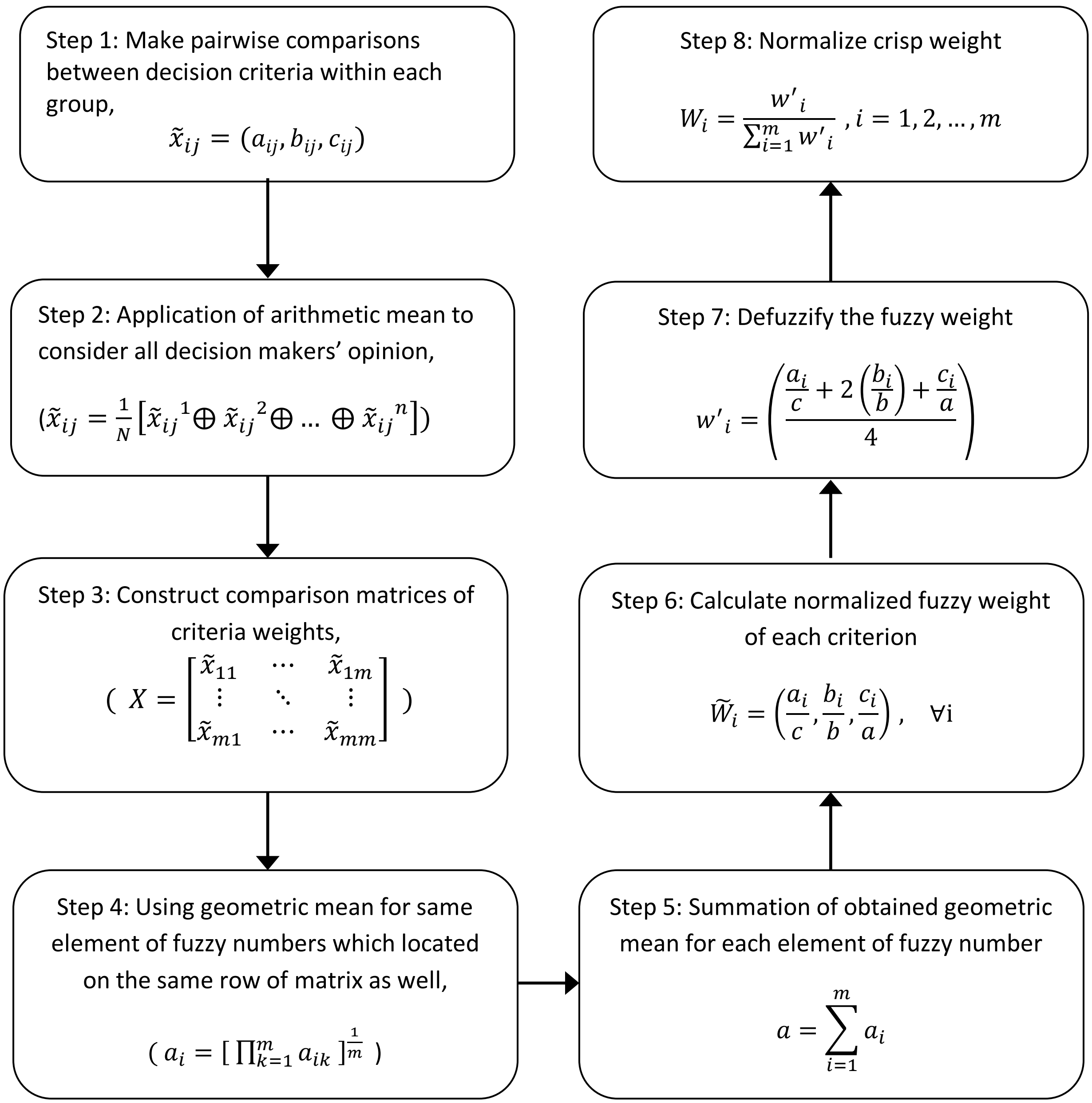


Figure 3.1. Summary of the selected procedure of pair-wise approach to calculate the weight of decision criteria within each group of criteria

3.3.2 Hierarchical Approach

The second approach is based on the main concept of a hierarchal process. In comparison to the pairwise approach, in this hierarchical approach decision makers assign a rating from predetermined linguistic fuzzy variables for each criterion without considering the absolute importance of other criteria. A similar method is used to calculate the weights of the different categories of decision criteria. As mentioned before, this research uses the fuzzy rates listed in Table 3.2. This approach is capable of dealing with large number of decision criteria and category of criteria.

The number of the decision criteria identified in this research as shown in Table 3.1 significantly favours the use of the hierarchical approach as the preferred method to compute the criteria weights. Furthermore, as part of the user input weighting exercise (the blank questionnaire forms Appendix A), which is described in following chapter, knowledgeable municipal engineers from mature municipalities were asked to assign their municipality's importance rating to each decision criterion. The composite scores were calculated by applying fuzzy linguistic variables as listed in Table.3.2 (i.e., very high to very low). Similar to the aforementioned pair-wise approach, it has been assumed that for the sake of simplification that the ratings from each decision maker from the individual municipalities are equally important.

The procedure and mathematical formulations of the hierarchical approach for computation of the weights are presented below.

Step 1. First step is to collect the decision makers' preferences.

Step 2. Second step is to apply the fuzzy multiplication. For each decision maker, the fuzzy score assigned by decision makers to the criterion is multiplied by the fuzzy score assigned to the related category of decision criteria. The formula of this step is as follow:

$$\tilde{S}_{ic} = \widetilde{W}_{ic} \otimes \widetilde{W}_{it} \qquad \textit{Equation 3.9}$$

Where $\widetilde{W}_{ic}$ and $\widetilde{W}_{it}$ denote the fuzzy score assigned by the i^{th} decision maker to c^{th} criterion and t^{th} category of criteria, respectively. Additionally, $\tilde{S}_{ic}$ denotes the overall fuzzy score assigned by the i^{th} decision maker to c^{th} criterion.

Step 3. This step is to calculate the average of fuzzy scores assign by all decision makers to c^{th} decision criterion that is denoted by $\tilde{S}_c$ .The mathematical formulation of this step is mentioned below.

$$\tilde{S}_c = \frac{1}{n}\left(\sum_{i=1}^{n} \tilde{S}_{ic}\right) \qquad \textit{Equation 3.10}$$

And

$$\tilde{S}_c = (a_c, b_c, c_c) \qquad \textit{Equation 3.11}$$

Where *n* denotes the number of decision makers.

Step 4. Through this step, the average fuzzy scores which are obtained from previous step are defuzzified. The mathematical formula of this step is as follow:

$$S_c = \left(\frac{a_c + 2 \times b_c + c_c}{4}\right) \qquad \textit{Equation 3.12}$$

Step 5. This step is to normalize the defuzzified scores obtained from Step 4.

$$S_c{}' = \left(\frac{S_c}{\sum_{c=1}^{m} S_c}\right) \qquad \textit{Equation 3.13}$$

Where m denotes the number of all decision criteria.

3.4. Evaluation of Alternatives

The identification and method of assigning the weights to evaluation decision criteria are discussed in the two previous sections of this chapter. In this section, the most important part of decision making is described: how alternatives can be effectively evaluated. As explained earlier, MCDM was selected as a preferred method from among the many existing decision-making methods discussed in section 2.4 of this thesis.

Among the different methods of the MCDM family described earlier, the TOPSIS method has been chosen as a prime candidate. The two main advantages of TOPSIS method are that it avoids cumbersome pairwise comparisons among alternatives and it provides the capability of working with the framework of a fuzzy environment, as discussed later in this section.

The general procedure for using TOPSIS is described using the eight steps already outlined in section 2.5.8, the literature review section of this thesis. That section describes how TOPSIS can work with fuzzy variables and, on top of that, how it can be incorporated with AHP.

Now, the procedure of applying a fuzzy TOPSIS method under group decision making is provided in the following 7 steps, as illustrated in Fig. 3.2:

Step 1. Assign a performance rating to alternatives by using linguistic fuzzy variables. In this section, and similar to the previous section, fuzzy variables with triangular membership functions are chosen. These fuzzy variables are listed in Table 3.3.

Table 3.3. Fuzzy linguistic variables for ratings the performance of alternatives

Very Low (VL)	(1, 1, 2)
Low (L)	(1, 2, 3)
Medium Low (ML)	(2, 3, 5)
Fair (F)	(3, 5, 7)
Medium High (MH)	(5, 7, 9)
High (H)	(7, 9, 10)
Very High (VH)	(9, 10, 10)

Step 2. Calculate the average of the given ratings by applying an arithmetic mean operation as follows:

$$\tilde{r}_{ij} = \frac{1}{P}\left[\tilde{r}_{ij}{}^{1} \oplus \tilde{r}_{ij}{}^{2} \oplus \dots \oplus \tilde{r}_{ij}{}^{p}\right] \qquad \textit{Equation 3.14}$$

Where *P* denotes the number of decision makers. $\tilde{r}_{ij}{}^{p}$ is a fuzzy number that denotes the evaluation of the p^{th} decision maker or expert on performance of the i^{th} alternative for j^{th} criterion.

Step 3. The obtained fuzzy numbers from the previous step can concisely be expressed in a matrix format that is usually called a decision matrix.

$$\widetilde{D} = \begin{bmatrix} \tilde{r}_{11} & \cdots & \tilde{r}_{1m} \\ \vdots & \ddots & \vdots \\ \tilde{r}_{p1} & \cdots & \tilde{r}_{pm} \end{bmatrix} \qquad \textit{Equation 3.15}$$

Where *m* denotes the number of criteria and *p* denotes the number of alternatives. In addition, $\widetilde{D}$ denotes the decision matrix including fuzzy variables.

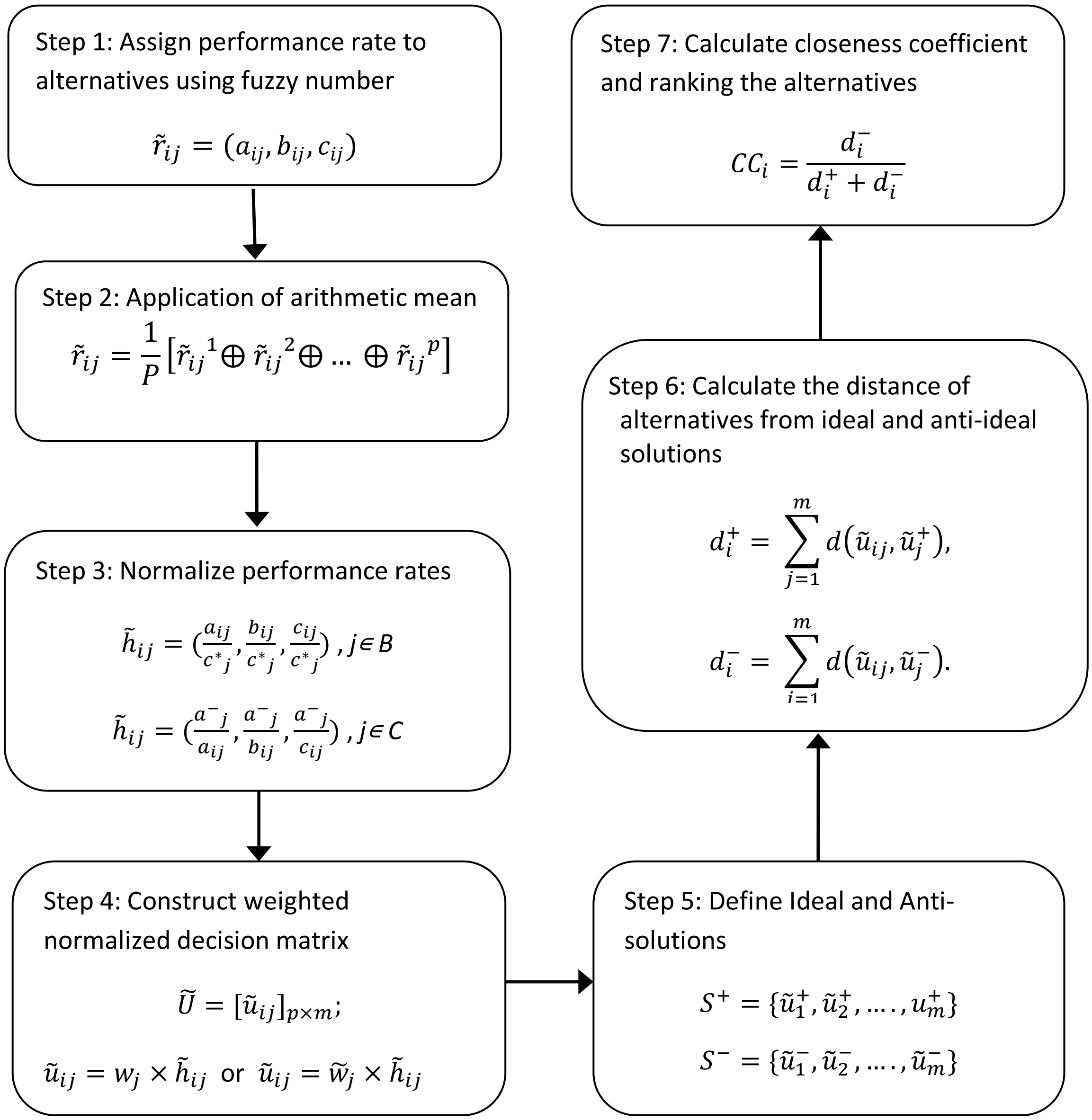


Figure 3.2. Stepwise proposed procedure for the evaluation of decision alternatives

Step 4. In this step, to provide consistency between the ratings, they must be normalized. At this point, two types of criteria need to be defined: cost and benefit. Benefit criteria are those which favour higher values, while cost criteria are those which favour lower values. Benefit and cost subsets of criteria are represented by *B* and *C*, respectively. The normalization method of the cost criteria is different from the benefit criteria:

$$\tilde{h}_{ij} = (\frac{a_{ij}}{c^{*}{}_{j}}, \frac{b_{ij}}{c^{*}{}_{j}}, \frac{c_{ij}}{c^{*}{}_{j}}), j \in B; \qquad \textit{Equation 3.16}$$

$$\tilde{h}_{ij} = (\frac{a^-{}_j}{a_{ij}}, \frac{a^-{}_j}{b_{ij}}, \frac{a^-{}_j}{c_{ij}}), j \in C; \quad \text{Equation 3.17}$$

$$c^*{}_j = \max_i c_{ij}, \text{ if } j \in B; \quad \text{Equation 3.18}$$

$$a^-{}_j = \max_i a_{ij}, if \in C. \quad \text{Equation 3.19}$$

Where *C* denotes the set of all cost decision criteria and *B* denotes the set of all benefit decision criteria. Additionally, $\tilde{h}_{ij}$ denotes the normalized performance rate of alternatives ($\tilde{r}_{ij}$).

Now, the normalized decision matrix can be constructed as follows:

$$\tilde{U} = [\tilde{u}_{ij}]_{p \times m}, i = 1,2 \ldots, p, j = 1,2, \ldots m; \quad \text{Equation 3.20}$$

$$\tilde{u}_{ij} = w_j \times \tilde{h}_{ij} \quad \text{Equation 3.21}$$

$$\tilde{u}_{ij} = \tilde{w}_j \times \tilde{h}_{ij} \quad \text{Equation 3.22}$$

Where $\tilde{U}$ denotes the weighted normalized decision matrix and w_j denotes the weight of criteria *j* as discussed before. Additionally, if fuzzy weights ($\tilde{w}_j$) are available, equation 3.17 also can be used to compute the weighted normalized performance rate of alternatives. At this stage, as shown in Equation 3.15, the weights of the decision criteria can be used in the decision-making matrix and in the evaluation of alternatives.

Step 5. After obtaining the normalized elements of the decision matrix from Step 4, the ideal and anti-ideal solutions can be identified and the total distance of each performance rating from each of these two specific solutions can be calculated so that preferences can be ranked. In order to provide a consistency between these solutions and the elements of a normalized decision making matrix, the ideal and anti-ideal solutions need to be fuzzy numbers with triangular membership function. Accordingly, the Fuzzy Positive Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS) are presented as follows:

$$S^+ = \{\tilde{u}_1^+, \tilde{u}_2^+, \ldots., \tilde{u}_m^+\}; \quad \text{Equation 3.23}$$

$$S^- = \{\tilde{u}_1^-, \tilde{u}_2^-, \ldots., \tilde{u}_m^-\}; \quad \text{Equation 3.24}$$

$$\{u^{+}{}_{1}, \dots, u^{+}{}_{m}\} = \{(max_j u_{ij} \big| \, j \in C_b), (min_j u_{ij} \big| \, j \in C_c)\};$$ *Equation 3.25*

$$\{u^{-}{}_{1}, \dots, u^{-}{}_{m}\} = \{(min_j u_{ij} \big| \, j \in C_b), (max_j u_{ij} \big| \, j \in C_c)\};$$ *Equation 3.26*

Where $S^{+}$and S^{-} denote FPIS and FNIS, respectively.

According to Chen (2000), after the calculation of the weighted normalized performance ratings have taken place, the fuzzy position and negative ideal solution with respect to each criterion can be calculated as follows:

$$\tilde{u}_j^{+} = (1.0, 1.0, 1.0), \; j = 1, 2, \dots, m;$$ *Equation 3.27*

$$\tilde{u}_j^{-} = (0.0, 0.0, 0.0), \; j = 1, 2, \dots, m;$$ *Equation 3.28*

Step 6. The following equations are used to calculate the distance of each alternative A_i *(i=1, 2… p)* from the ideal and anti-ideal solutions:

$$d_i^{+} = \sum_{j=1}^{m} d(\tilde{u}_{ij}, \tilde{u}_j^{+}), \forall i = 1,2, \dots, p,$$ *Equation 3.29*

$$d_i^{-} = \sum_{j=1}^{m} d(\tilde{u}_{ij}, \tilde{u}_j^{-}), \forall i = 1,2, \dots, p,$$ *Equation 3.30*

Where $d(\tilde{u}_{ij}, \tilde{u}_j^{+})$ denotes the distance of the *jth* performance rating of *ith* alternative from ideal solution. Similarly, $d(\tilde{u}_{ij}, \tilde{u}_j^{-})$ denotes the distance of the j^{th} performance rating of the i^{th} alternative from the anti-ideal solution. Both d_i^{+} and d_i^{-} represent the total distance of the i^{th} alternative from the ideal and anti-ideal solutions, respectively.

Step 7. In this step, the closeness coefficient can be calculated in order to obtain a consistent index for comparing the alternatives of a decision-making problem. The closeness coefficient of each alternative is calculated as:

$$CC_i = \frac{d_i^{-}}{d_i^{+} + d_i^{-}}, \forall i = 1,2, \dots, p.$$ *Equation 3.31*

As it is described in the literature review section of this thesis, the alternative with the farthest distance from the anti-ideal solution and closest to the ideal solution is the most favorable. Accordingly, the alternative with the higher value of closeness coefficient has better efficiency than an alternative with a lower value of closeness coefficient. So, in the end, by applying closeness coefficient values, the various alternatives of a decision making problem can be ranked with respect to the defined evaluation criteria.

Likewise, as discussed in the previous section, all stages required for the calculation of alternative evaluation are depicted in Fig.3.2.

Chapter 4 Survey and Results

In the first two chapters, the main objectives of this research have been discussed. Chapter 1 describes the decision-making method selected for this research, and chapter 2 outlines the rationale (also known as "the why"). Chapter 3 presented the mathematical formulations and stepwise procedures of the preferred decision-making method. Here, Chapter 4 provides a description of the survey that was performed as part of the methodology of this research. This chapter begins with a brief introduction of the survey, proceeds with the required process and presents figures of the received survey responses. The results are presented in the last section of this chapter.

4.1. Introduction

This survey, as part of the methodology of this research, has been designed and implemented to obtain responses from a number of Canadian municipalities. The main objective of this survey is to incorporate real-world experience from Canadian municipalities and compare the results with theoretical opinions and hypotheses. This survey includes 17 questions (included as Appendix A), starting with a number of general questions and followed by more detailed questions regarding the municipalities' preferences and priorities when it comes to selecting which infrastructure projects should be implemented.

4.2. Process of the Survey

This survey has been created and developed using eight main sequential steps, as shown in Fig. 4.1 and described as follows:

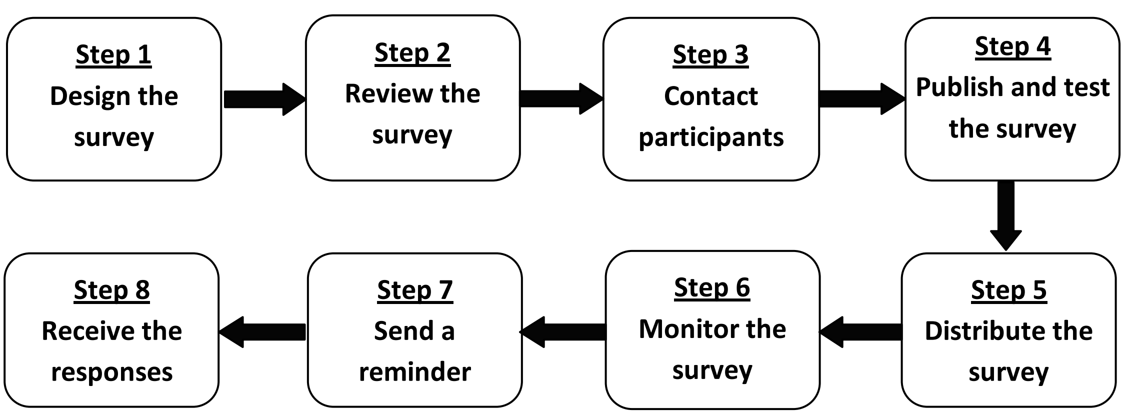


Figure 4.1. Main steps of the survey procedure

Step 1. Design the survey: the content and type of questions were initially decided in this step. The survey was divided into three main sections. The initial section includes general information about the participants and their relevant technical experience. The middle section consists of a series of questions about significant factors that can affect the decision making directly. The last section is mainly about the similarities or differences between decision criteria for the selection of specific municipal infrastructure projects, as well as about the complexity of the decision making process. Most questions in this survey have multiple choice answers and only a few questions were "open-ended" or requested respondent comments. For the convenience of the respondents, the survey was designed to be web based and to be compatible with mobile devices (e.g., iPhone and iPad) as well as both PC and Mac computers.

Step 2. **Review the survey:** as the second step, the questions of this survey were reviewed several times by a UBC research team in order to cover important perspectives of infrastructure asset decision making. The survey was intentionally kept simple and clear, focusing mainly on the objectives of this study. The survey was also *alpha*-tested by the research team (three individuals). After their suggested changes were implemented, this was followed by a final *beta*-test performed by same research team.

Step 3. **Contact participants**: before distributing the survey, an email was sent to prospective municipality (each municipal representative having relevant experience in asset management) asking their municipality's interest in taking part in this survey. The prospective municipalities were selected by the research team from a representative sample of mature organization in Canada with sophistication in infrastructure management. Those municipalities which agreed to participate in the survey are called participants.

Step 4. **Publish and test the survey:** after reviewing the responses from the *beta* test and editing the questions, the survey was finalized and was made available on the Internet. The URL of the website for the survey is a link providing direct access to the survey for the participants. To ensure that the survey website performed as expected, the link was pretested by all research team members.

Step 5. Distribute the survey: after receiving permission to proceed from the survey participants, the survey URL was distributed electronically via an email sent to each participant. It was believed that generally web-based surveys are more convenient to work with rather than paper-based, telephone call-based, and face-to-face surveys. Using a web-based survey, participants have enough time to think about the questions, to refer to any reference materials, and to consult with other engineers and asset managers regarding their municipality's priorities. These additional potential steps can increase the chance of receiving more reliable and thoughtful responses from the participants. Additionally, the web-based survey tool that was selected used facilitated a more efficient way of monitoring and maintaining the survey (Medin et al., 1999; van Selm and Jankowski, 2006).

Step 6. Monitor the survey: Through this step, the survey responses were monitored and the survey tool confirmed whether all emails were sent to the correct addresses and whether the participants received the emails, or not. Additionally, in order to verify that the survey was distributed correctly, an similar email was sent to all research team members. Respondents were also told that they could ask for more explanations or clarifications from research team if anything in the survey was not clear enough to them. The survey host website (Vovici 2012) is able to save the participants' responses and retrieve them at later times in case the survey was not filled out in one sitting by a participant.

Step 7. Send a reminder: approximately one week after the original email in Step 5 was sent, a reminder was forwarded to those who had not yet submitted their responses. In doing so, six more participants submitted their responses on the next business day after receiving the reminder.

Step 8. Receive the responses: the date and time of the initial contacts were stored when the respondents clicked on the link of the survey for the first time. The participants were able to change or modify their responses any time after the initial submission. Several times during the elapsed time, the available responses were exported and stored as an excel spreadsheet; this indicated who submitted the survey, as well as who updated his/her responses and the date/time of that update.

4.3. Survey Results

The survey was sent to 19 individuals in 19 different municipalities, 13 responses were received and deemed to be complete; this indicates that 68 percent of respondents responded to the survey request.

The survey included 17 questions, as shown in Appendix A. The first four questions pertained to respondents' personal information; these responses were collected for administrative reasons and are not presented in the findings in order to keep the individuals anonymous.

Question 4 (Q4) The average relevant experience of participants to the survey was roughly 10 to 20 years; this indicates that it is a significantly mature group with only two participant having less than 10 years of experience. Fig. 4.2 breaks down the response with respect to the relevant experience of the participants.

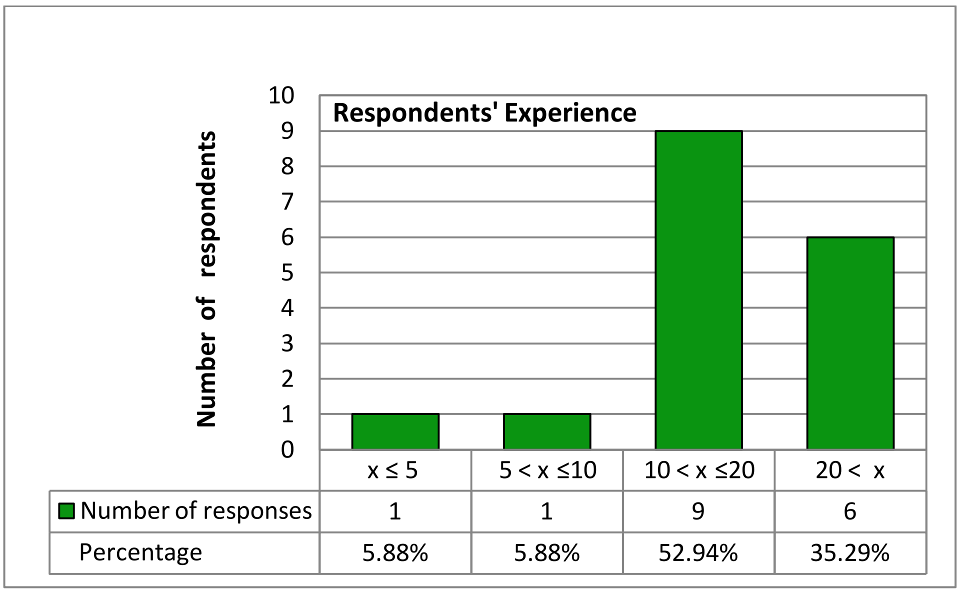
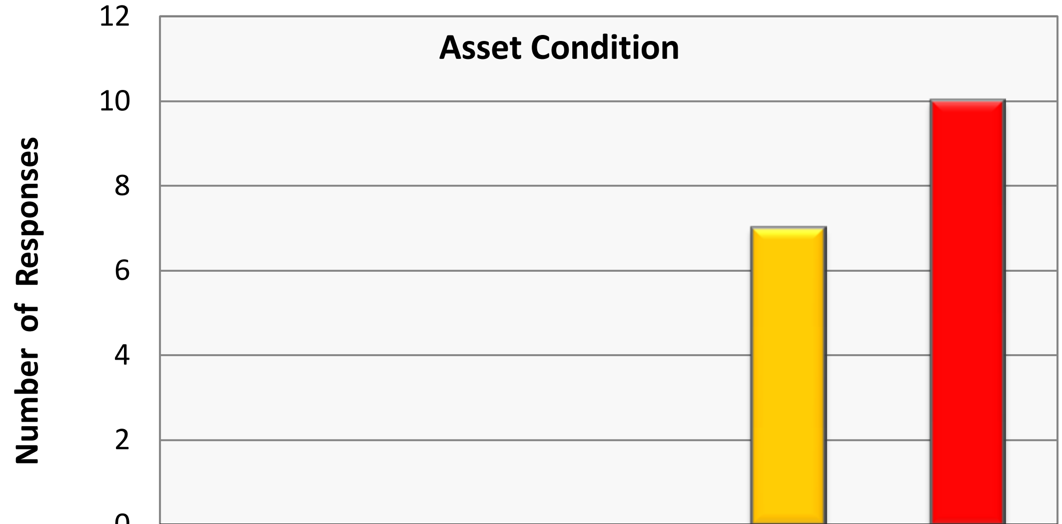


Figure 4.2. Break down the respondents according to their relevant years of experience

Question 5 informed the respondents that if they are not currently with a municipality that they should refer to their previous experience with a municipality or to their advice that they would provide to municipalities as a consultant. Question 17 asked respondents to specify any additional comments about this survey.

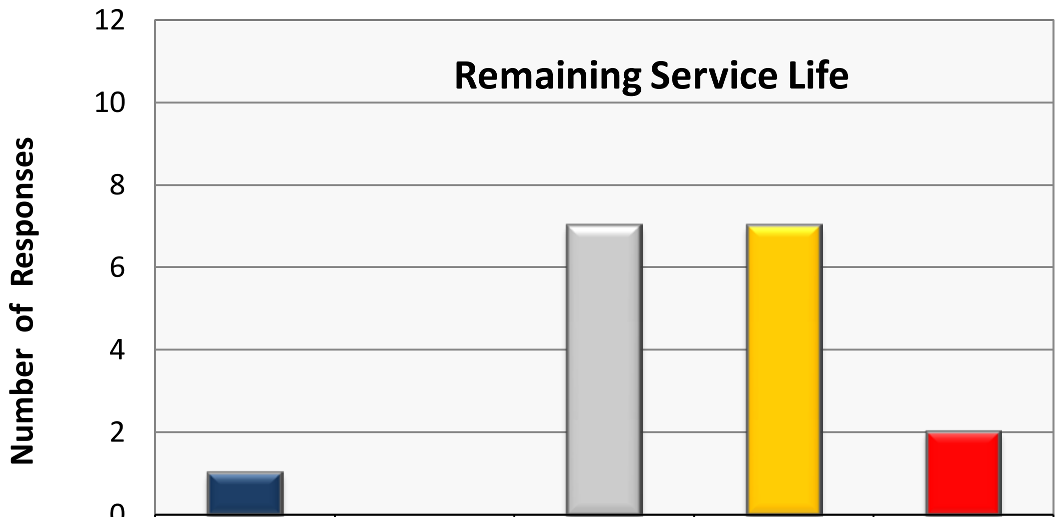
The survey results for questions 6 to 11—those directly related to the scope of this research—are presented in Figs. 4.3 to 4.33. Participants were asked to rate the given criteria on each question by considering its relative importance for the selection of municipal infrastructure projects, based on their municipality's priorities. The scores assigned to all decision criteria and the categories of decision criteria are presented in Table A.1.

Question 6 determines the relative importance of the technical and engineering decision criteria, including "asset condition", "remaining service life", "asset age", "level of service", "deterioration rate", "maintainability", "risk of failure", and "constructability" (see table 3.1). The responses for each of the aforementioned technical and engineering decision criterion are presented as Figs. 4.3 to 4.10, respectively.



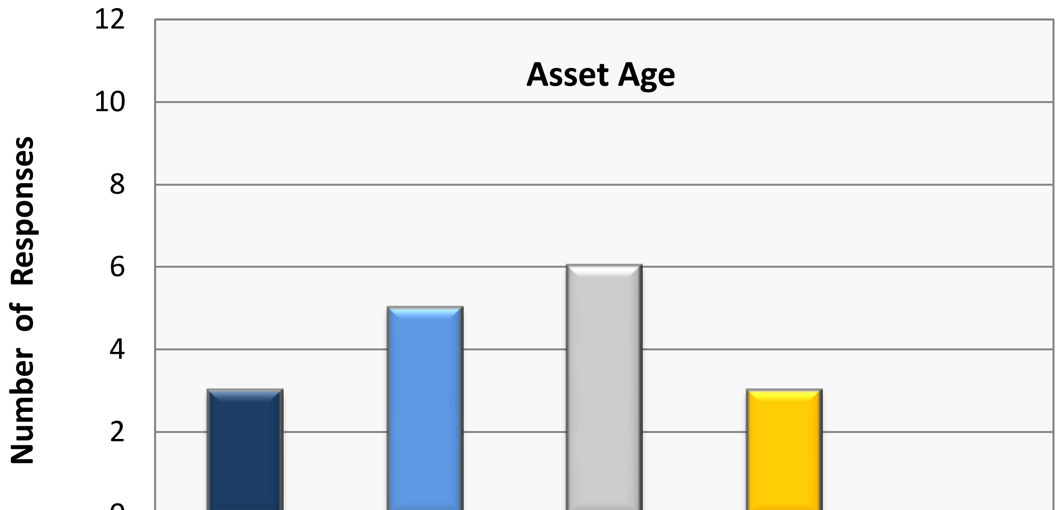
	Very low	Low	Medium	High	Very High
Number of Resp.	0	0	0	7	10
Percentage	0.0%	0.0%	0.0%	41.2%	58.8%

Figure 4.3. Given rates to asset condition criterion by survey participants



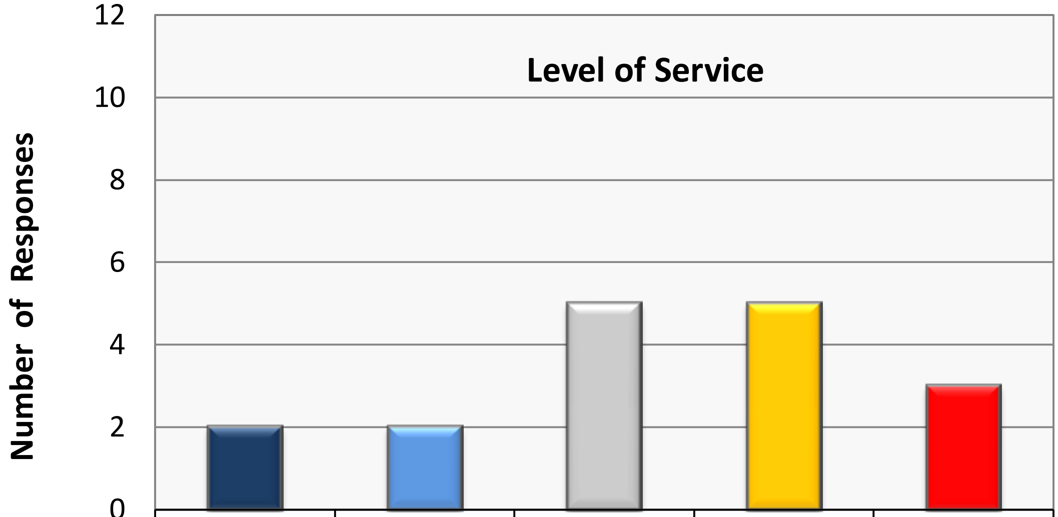
	Very low	Low	Medium	High	Very High
Number of Resp.	1	0	7	7	2
Percentage	5.9%	0.0%	41.2%	41.2%	11.8%

Figure 4.4. Given rates to remaining service life criterion by survey participants



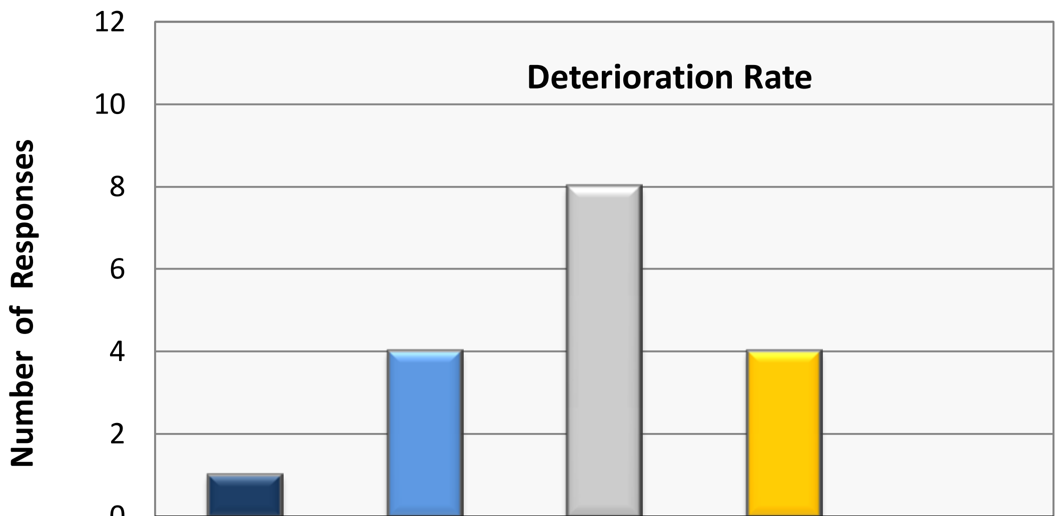
	Very low	Low	Medium	High	Very High
Number of Resp.	3	5	6	3	0
Percentage	17.6%	29.4%	35.3%	17.6%	0.0%

Figure 4.5. Given rates to asset age criterion by survey participants



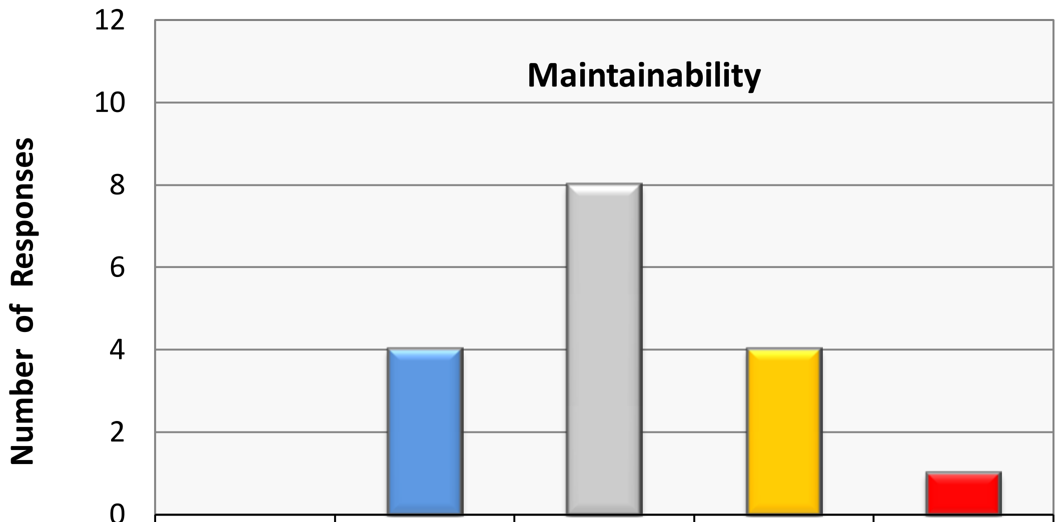
	Very low	Low	Medium	High	Very High
Number of Resp.	2	2	5	5	3
Percentage	11.8%	11.8%	29.4%	29.4%	17.6%

Figure 4.6. Given rates to level of service criterion by survey participants



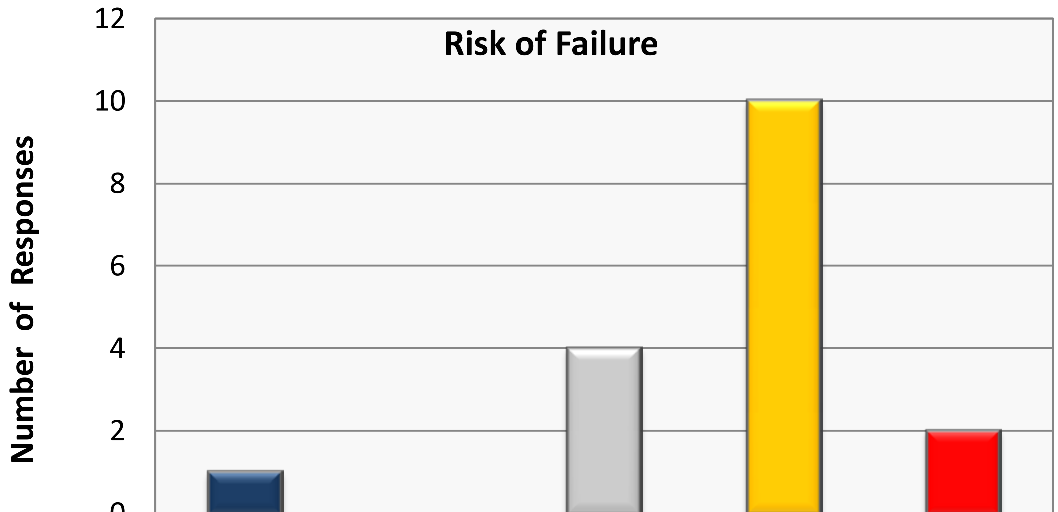
	Very low	Low	Medium	High	Very High
Number of Resp.	1	4	8	4	0
Percentage	5.9%	23.5%	47.1%	23.5%	0.0%

Figure 4.7. Given rates to deterioration rate criterion by survey participants



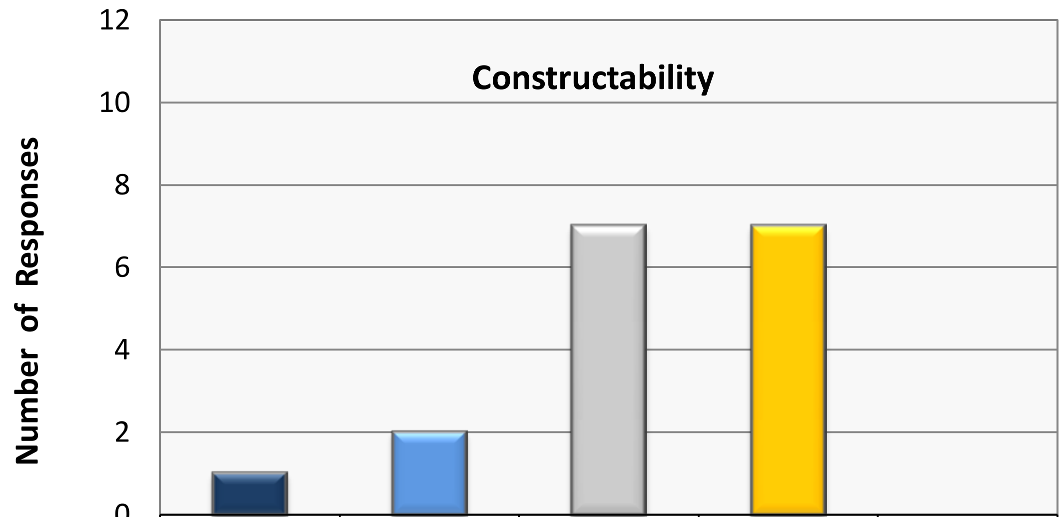
	Very low	Low	Medium	High	Very High
Number of Resp.	0	4	8	4	1
Percentage	0.0%	23.5%	47.1%	23.5%	5.9%

Figure 4.8. Given rates to maintainability criterion by survey participants



	Very low	Low	Medium	High	Very High
Number of Resp.	1	0	4	10	2
Percentage	5.9%	0.0%	23.5%	58.8%	11.8%

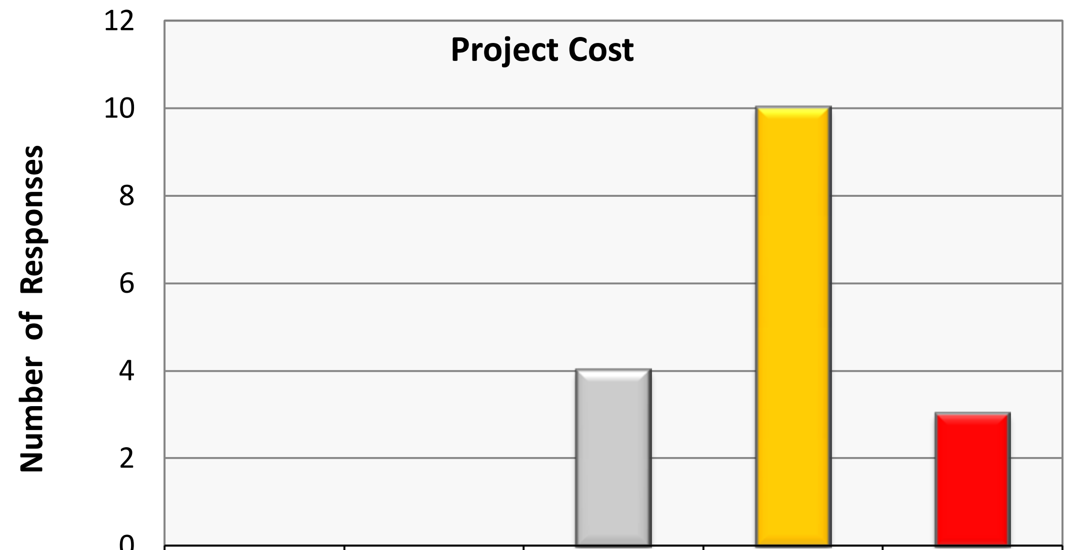
Figure 4.9. Given rates to risk of failure criterion by survey participants



	Very low	Low	Medium	High	Very High
Number of Resp.	1	2	7	7	0
Percentage	5.9%	11.8%	41.2%	41.2%	0.0%

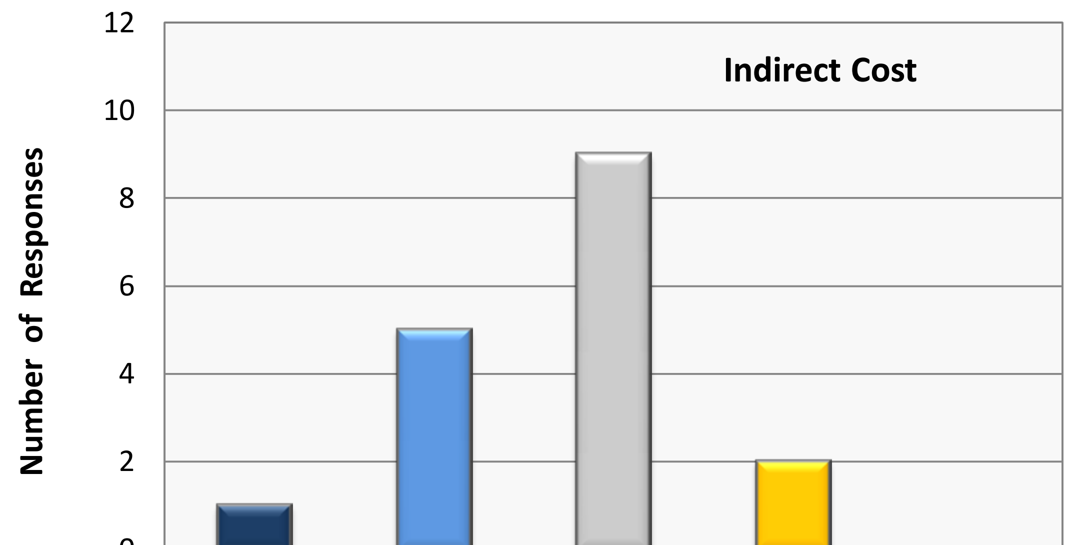
Figure 4.10. Given rates to constructability criterion by survey participants

Respondents are asked to rate the relative importance of provided economic decision criteria in question 7. These criteria are “project cost”, “indirect cost”, “agency cost/benefit”, “social cost/ benefit”, and “user cost/benefit”. Figs. 4.11 to 4.15 present these responses.



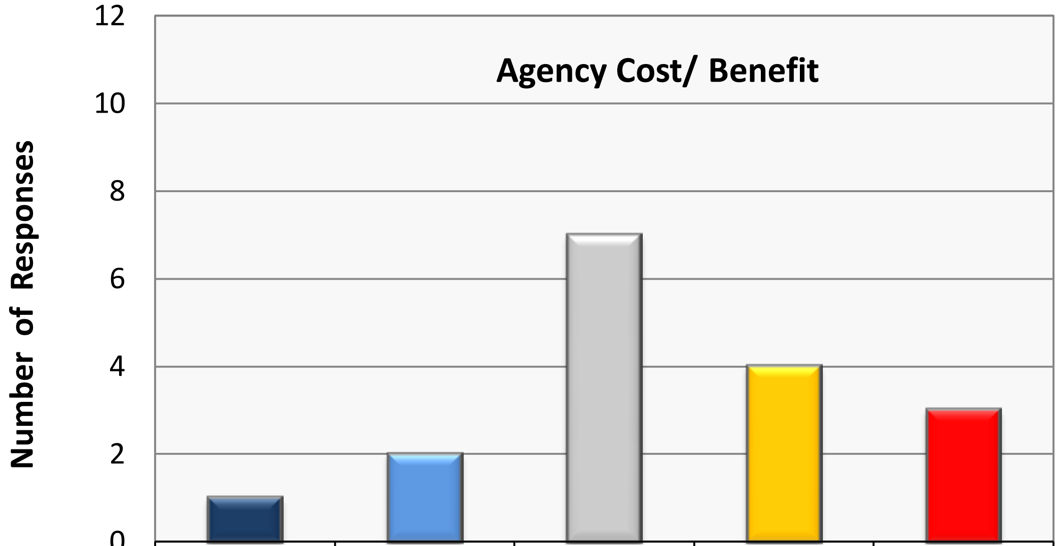
	Very low	Low	Medium	High	Very High
Number of Resp.	0	0	4	10	3
Percentage	0.0%	0.0%	23.5%	58.8%	17.6%

Figure 4.11. Given rates to project cost criterion by survey participants



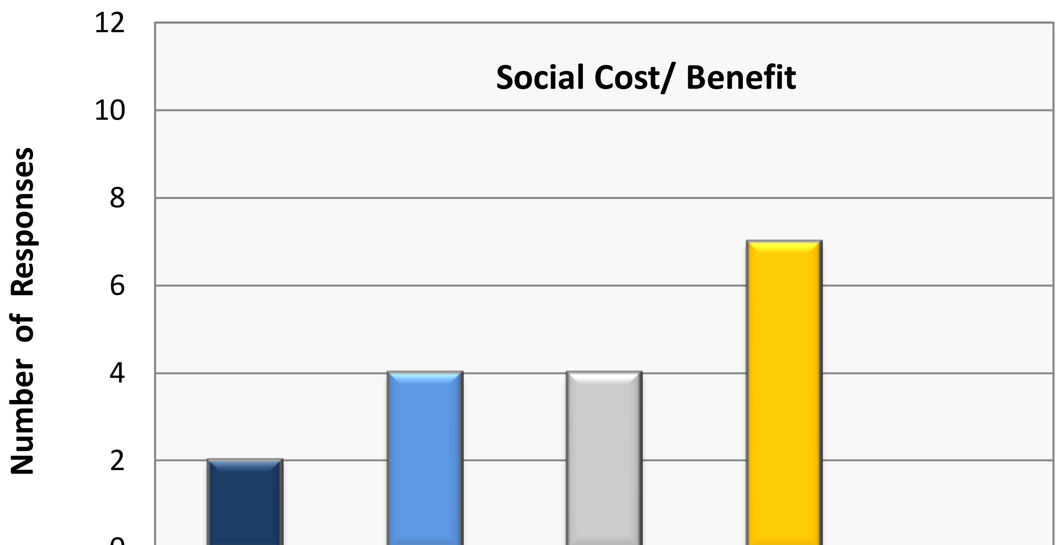
	Very low	Low	Medium	High	Very High
Number of Resp.	1	5	9	2	0
Percentage	5.9%	29.4%	52.9%	11.8%	0.0%

Figure 4.12. Given rates to indirect cost criterion by survey participants



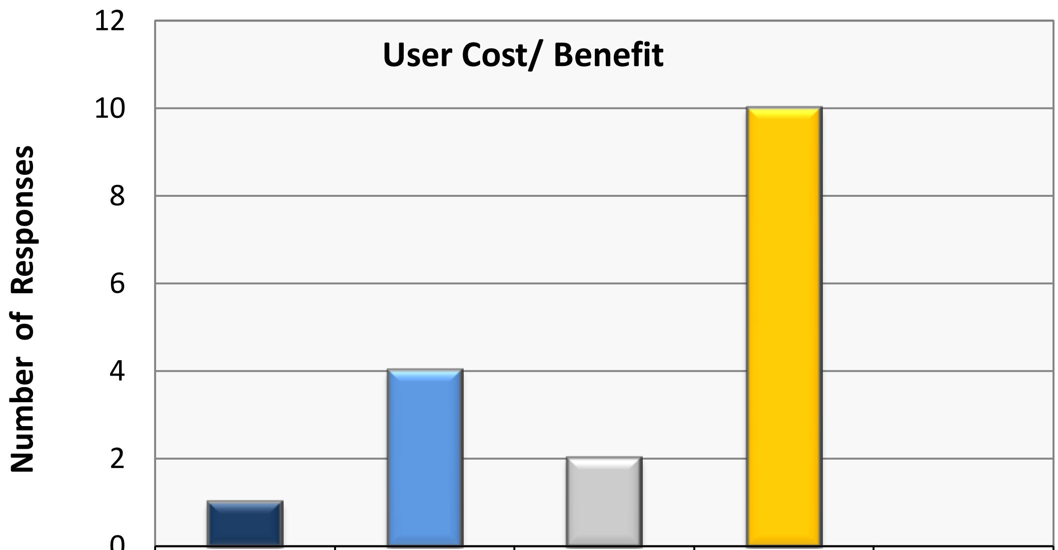
	Very low	Low	Medium	High	Very High
Number of Resp.	1	2	7	4	3
Percentage	5.9%	11.8%	41.2%	23.5%	17.6%

Figure 4.13. Given rates to agency cost/ benefit criterion by survey participants



	Very low	Low	Medium	High	Very High
Number of Resp.	2	4	4	7	0
Percentage	11.8%	23.5%	23.5%	41.2%	0.0%

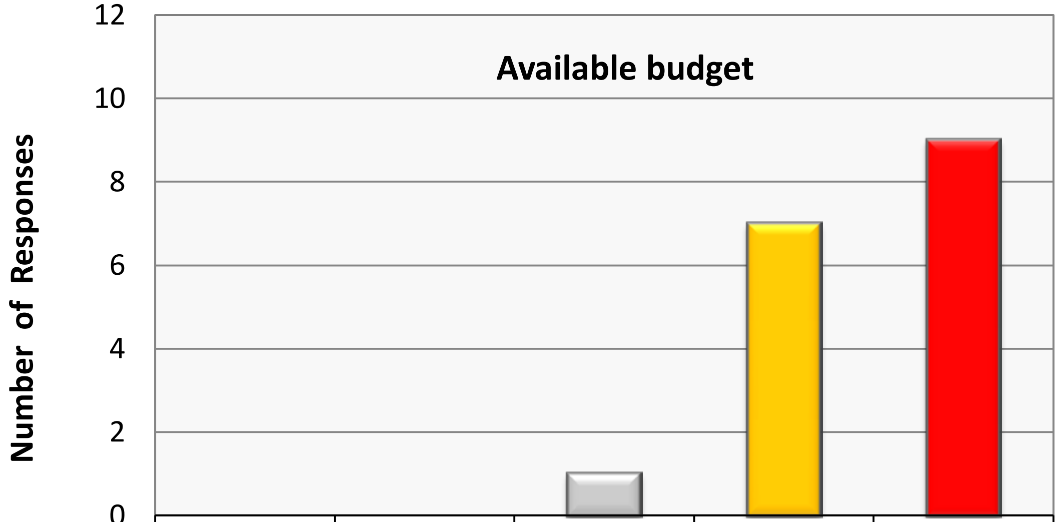
Figure 4.14. Given rates to social cost/ benefit criterion by survey participants



	Very low	Low	Medium	High	Very High
Number of Resp.	1	4	2	10	0
Percentage	5.9%	23.5%	11.8%	58.8%	0.0%

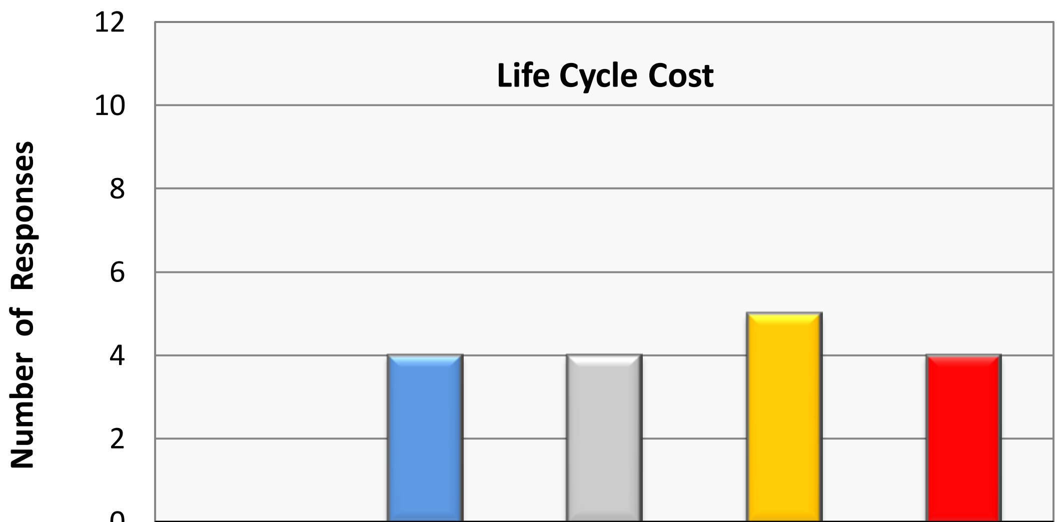
Figure 4.15. Given rates to user cost/ benefit criterion by survey participants

Question 8 deals with the financial decision criteria, which are becoming increasingly important for municipalities. These criteria include “available budget”, “life cycle cost”, “financial risk” and “asset value”. Similar to the previous questions, this question requested respondents to rank the relative importance of aforementioned criteria from their perspective. The results are illustrated in Figs. 4.16 to 4.19.



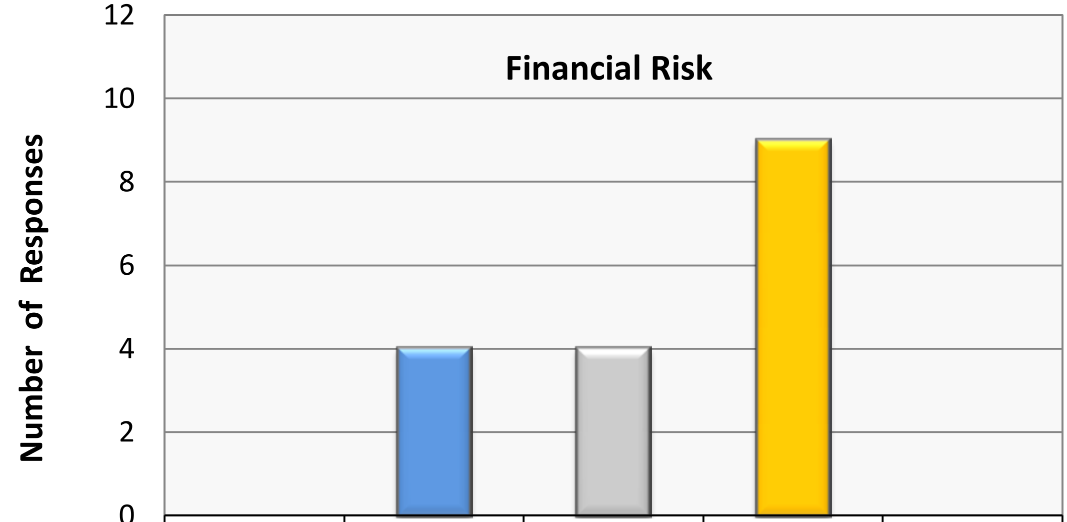
	Very low	Low	Medium	High	Very High
Number of Resp.	0	0	1	7	9
Percentage	0.0%	0.0%	5.9%	41.2%	52.9%

Figure 4.16. Given rates to available budget criterion by survey participants



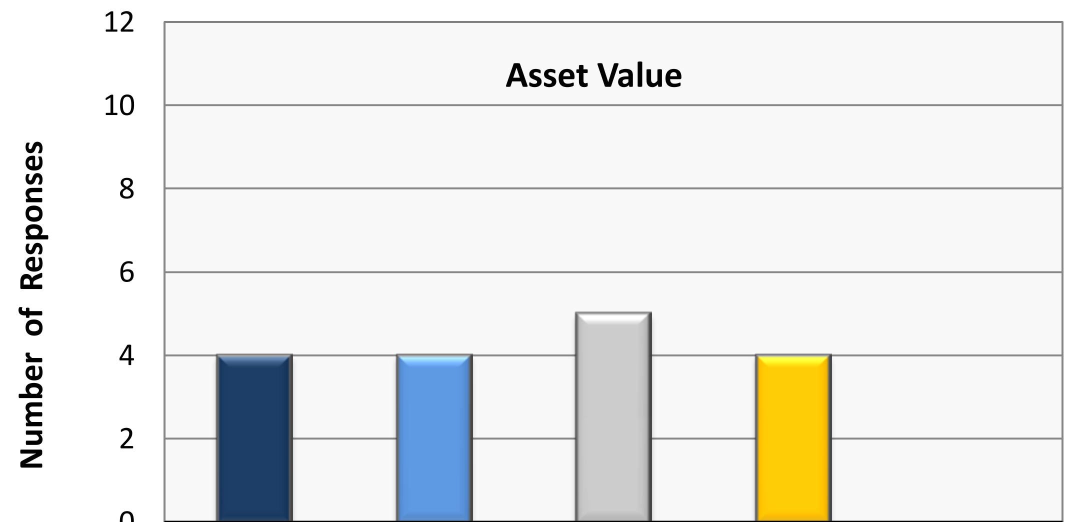
	Very low	Low	Medium	High	Very High
Number of Resp.	0	4	4	5	4
Percentage	0.0%	23.5%	23.5%	29.4%	23.5%

Figure 4.17. Given rates to life cycle cost criterion by survey participants



	Very low	Low	Medium	High	Very High
Number of Resp.	0	4	4	9	0
Percentage	0.0%	23.5%	23.5%	52.9%	0.0%

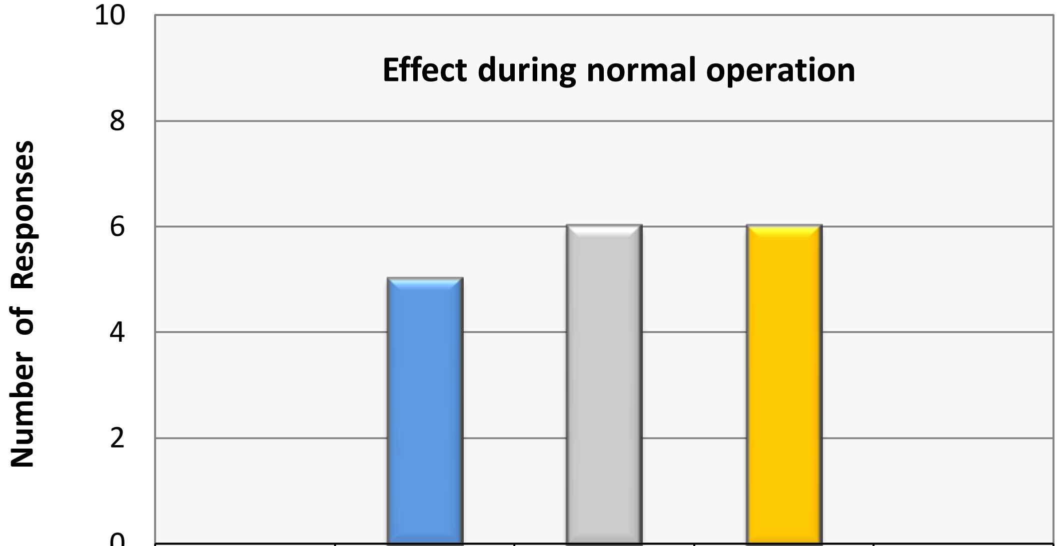
Figure 4.18. Given rates to financial risk criterion by survey participants



	Very low	Low	Medium	High	Very High
Number of Resp.	4	4	5	4	0
Percentage	23.5%	23.5%	29.4%	23.5%	0.0%

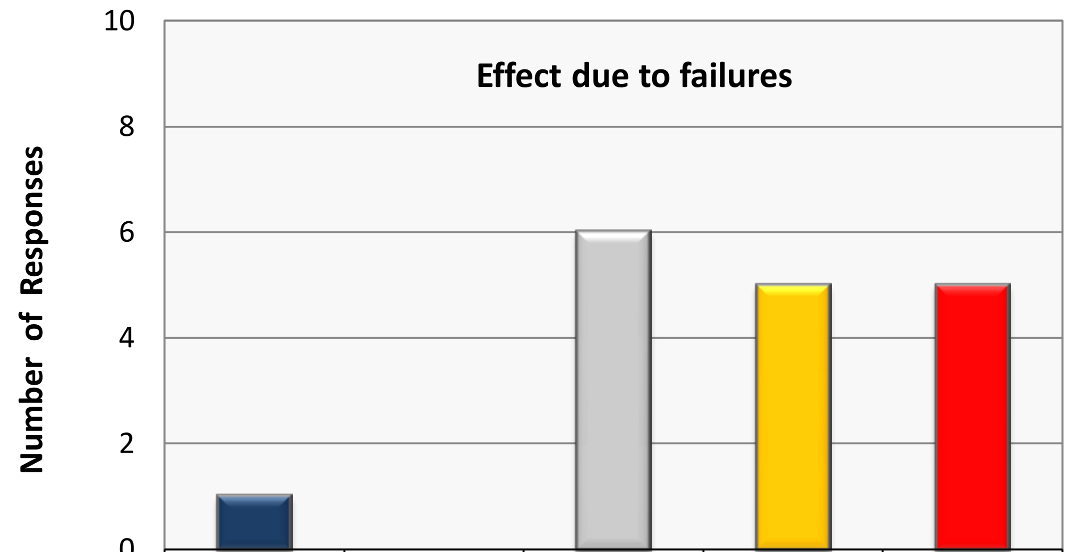
Figure 4.19. Given rates to asset value criterion by survey participants

Question 9 deals with environmental decision criteria which are becoming increasingly important to municipalities. These criteria include “effect during normal operation”, “effect due to failures”, and "effect during construction". Similar to the previous questions, this question queried respondents to select the relative importance of the aforementioned criteria from their municipality's perspective. The results are illustrated in Figs. 4.20 to 4.22.



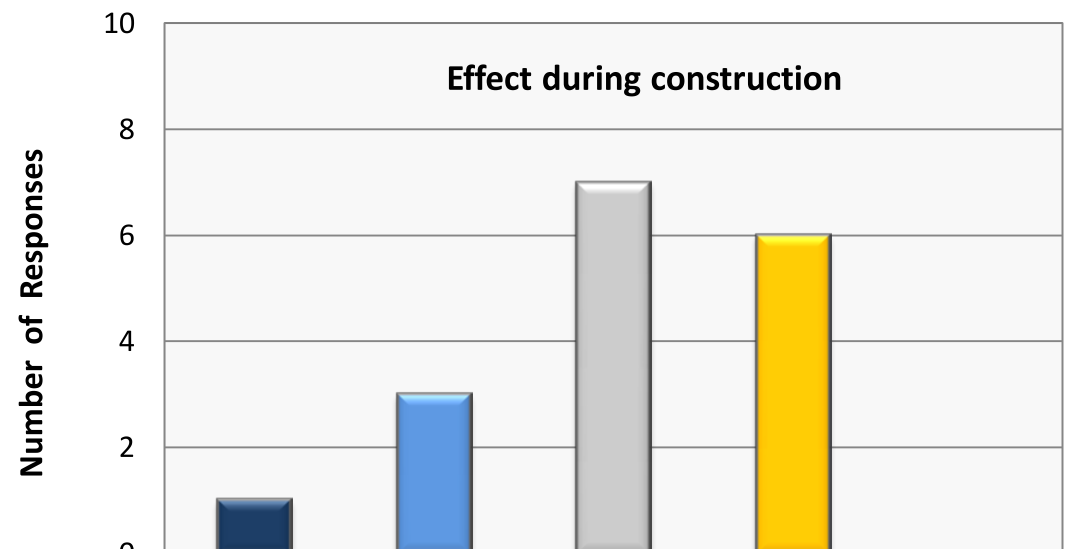
	Very low	Low	Medium	High	Very High
Number of Resp.	0	5	6	6	0
Percentage	0.0%	29.4%	35.3%	35.3%	0.0%

Figure 4.20. Given rates to the effect during normal operation criterion by survey participants



	Very low	Low	Medium	High	Very High
Number of Resp.	1	0	6	5	5
Percentage	5.9%	0.0%	35.3%	29.4%	29.4%

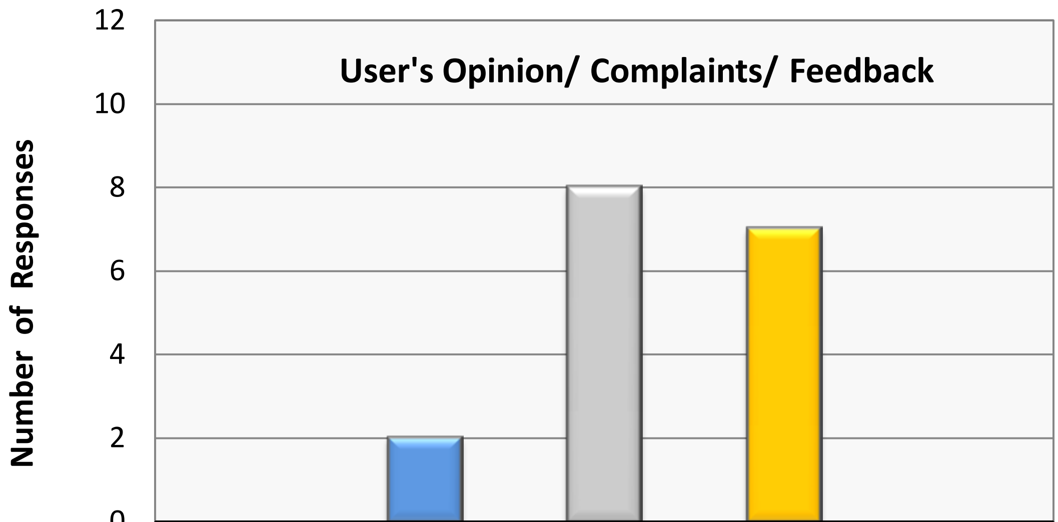
Figure 4.21. Given rates to effect due to failure criterion by survey participants



	Very low	Low	Medium	High	Very High
Number of Resp.	1	3	7	6	0
Percentage	5.9%	17.6%	41.2%	35.3%	0.0%

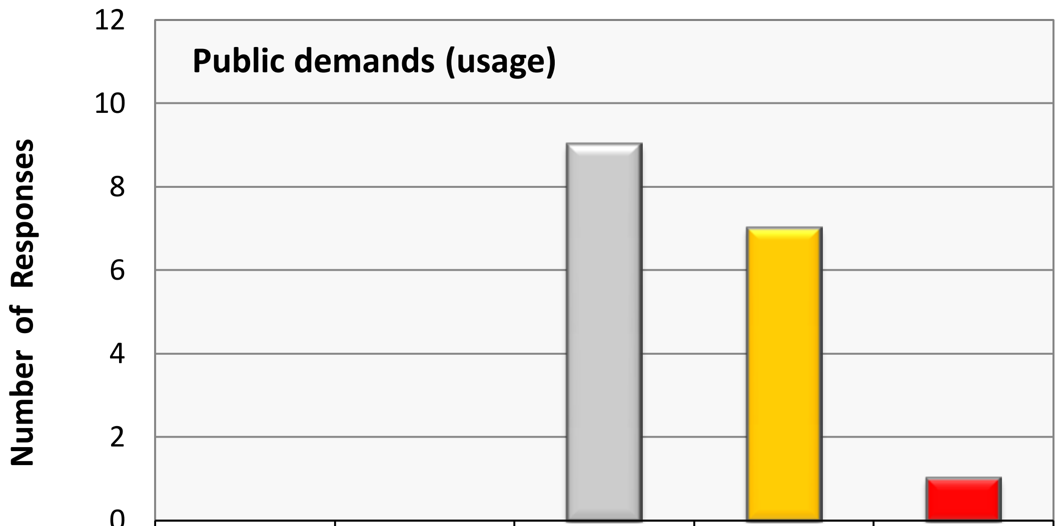
Figure 4.22. Given rates to effect during construction criterion by survey participants

In question 10, respondents were asked to rate the social decision criteria that can be used to select municipal infrastructure projects. These social criteria are “User's Opinion/Complaints/ feedback”, “Public demands (usage)”, “Proximity of project to major urban areas”, “Geographical distribution of funds”, “Safety”, and “Effect during operations”. Their responses are shown in Figs. 4.23 to 4.28.



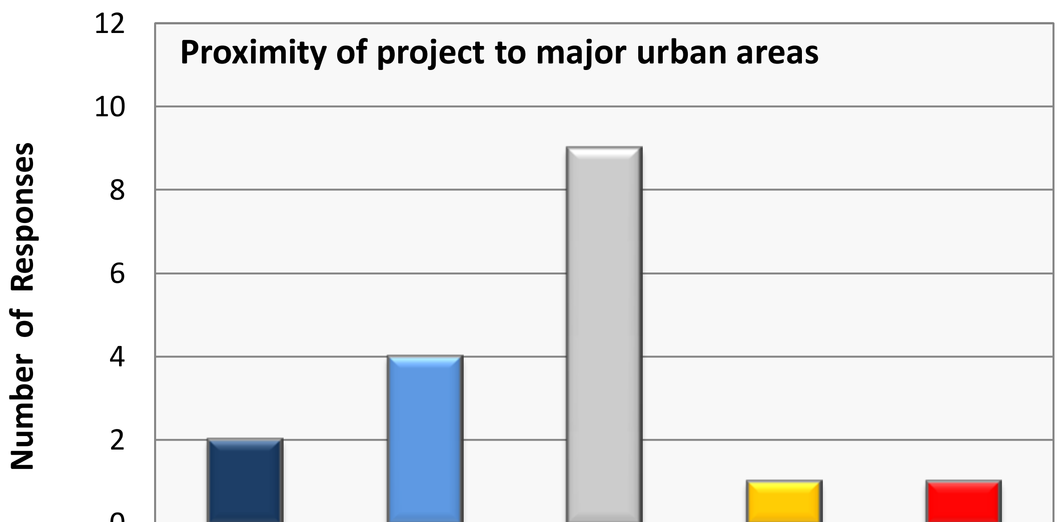
	Very low	Low	Medium	High	Very High
Number of Resp.	0	2	8	7	0
Percentage	0.0%	11.8%	47.1%	41.2%	0.0%

Figure 4.23. Given rates to user’s opinion/ complaints/ feedback criterion by survey participants



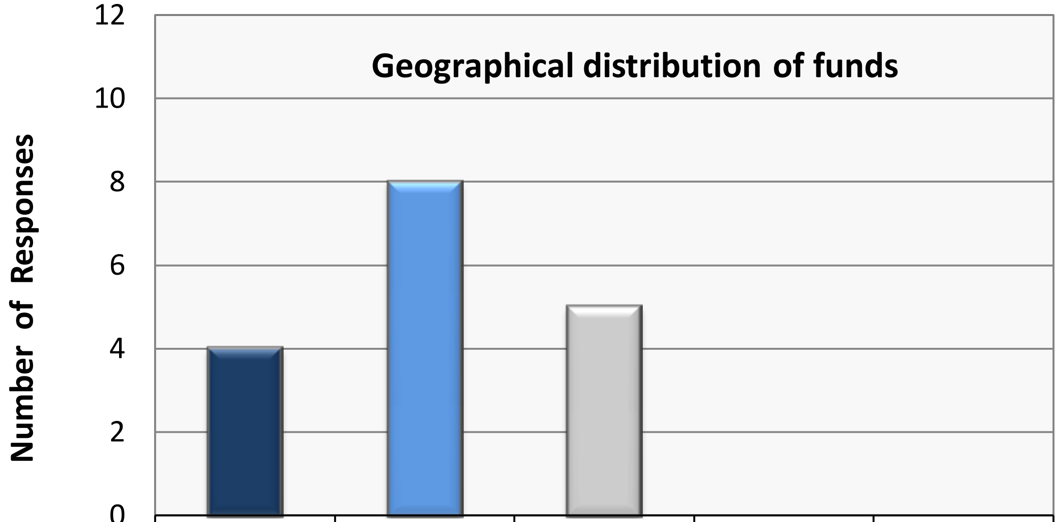
	Very low	Low	Medium	High	Very High
Number of Resp.	0	0	9	7	1
Percentage	0.0%	0.0%	52.9%	41.2%	5.9%

Figure 4.24. Given rates to public demands criterion by survey participants



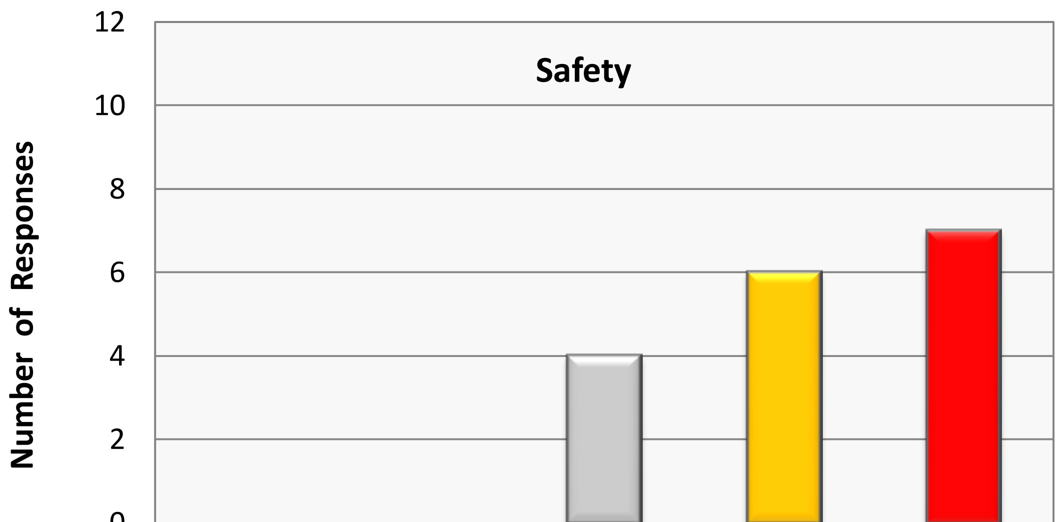
	Very low	Low	Medium	High	Very High
Number of Resp.	2	4	9	1	1
Percentage	11.8%	23.5%	52.9%	5.9%	5.9%

Figure 4.25. Given rates to proximity of project to major urban areas criterion by survey participants



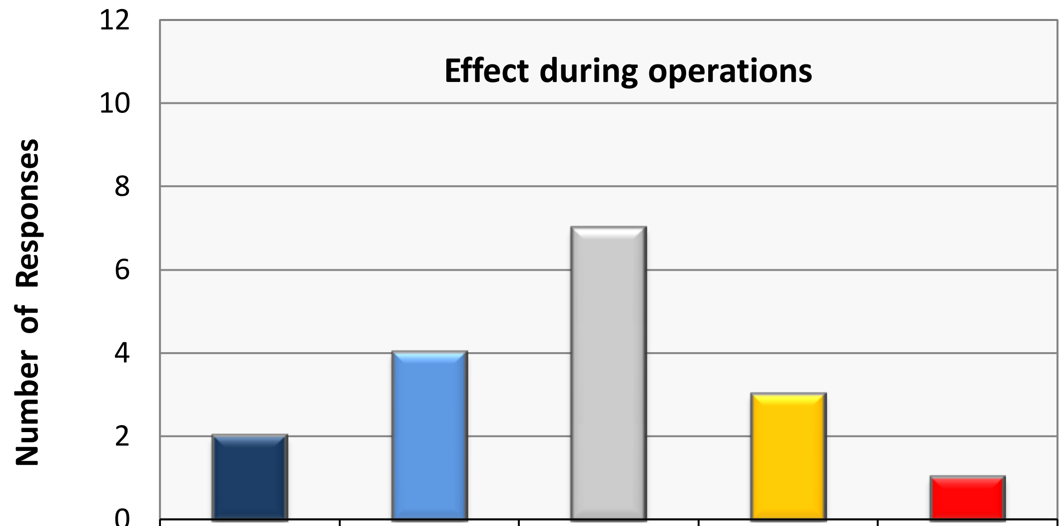
	Very low	Low	Medium	High	Very High
Number of Resp.	4	8	5	0	0
Percentage	23.5%	47.1%	29.4%	0.0%	0.0%

Figure 4.26. Given rates to geographical distribution of funds criterion by survey participants



	Very low	Low	Medium	High	Very High
Number of Resp.	0	0	4	6	7
Percentage	0.0%	0.0%	23.5%	35.3%	41.2%

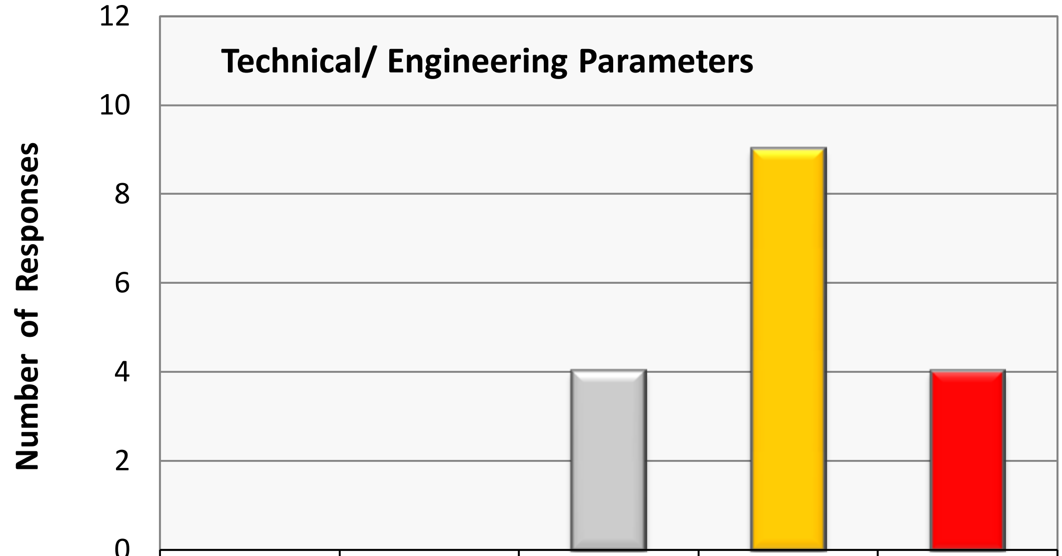
Figure 4.27. Given rates to safety criterion by survey participants



	Very low	Low	Medium	High	Very High
Number of Resp.	2	4	7	3	1
Percentage	11.8%	23.5%	41.2%	17.6%	5.9%

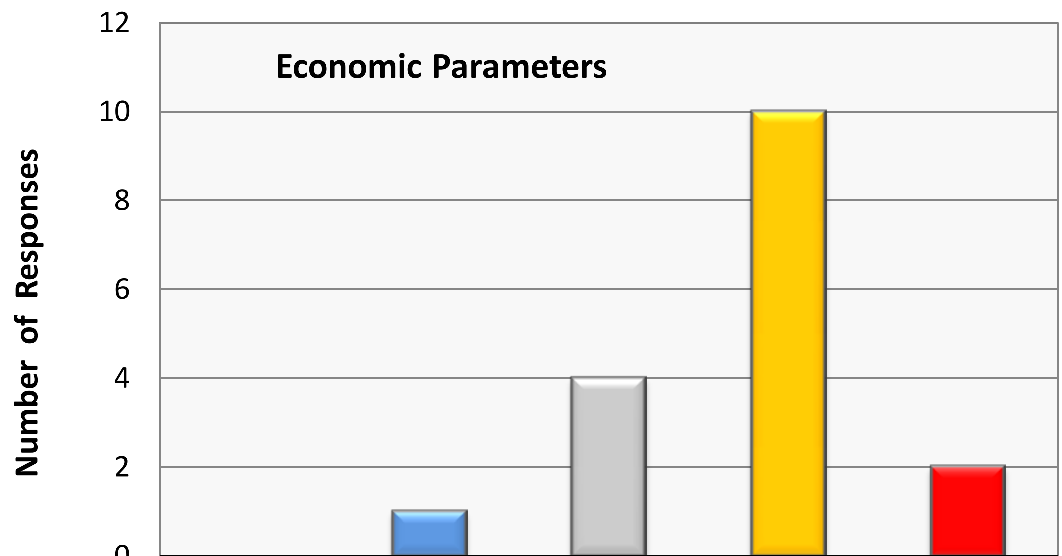
Figure 4.28. Given rates to effect during operation criterion by survey participants

In question 11, the respondents were asked to specify the relative importance of the general categories of decision criteria used for selection of municipal infrastructure projects. As mentioned earlier, these categories are “Technical/ Engineering Parameters”, “Economic Parameters”, “Financial Parameters”, “Environmental Parameters”, and “Social Parameters”. Figs. 4.29 to 4.33 schematically show the respondents’ opinion.



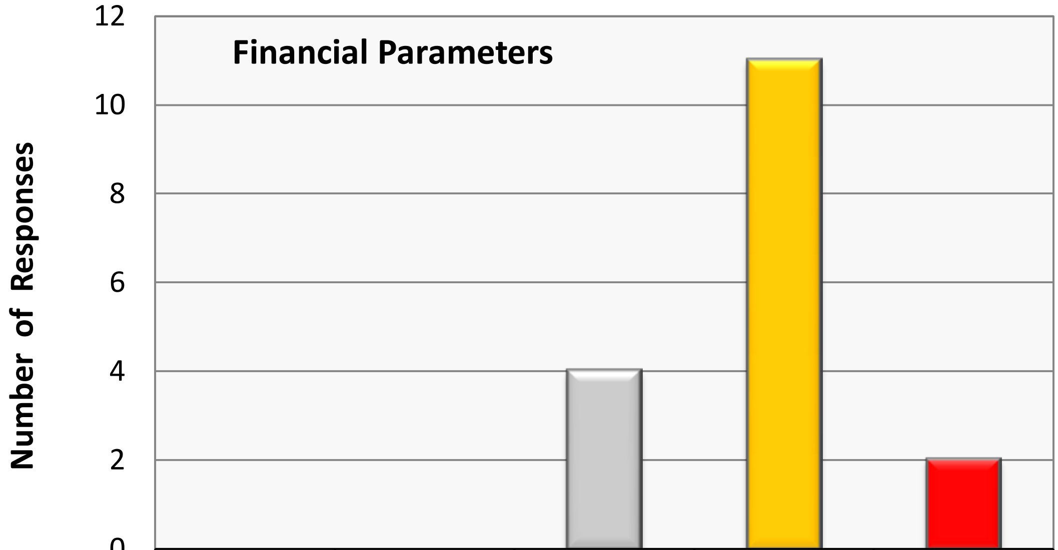
	Very low	Low	Medium	High	Very High
Number of Resp.	0	0	4	9	4
Percentage	0.0%	0.0%	23.5%	52.9%	23.5%

Figure 4.29. Given rates to technical/ engineering parameters category by survey participants



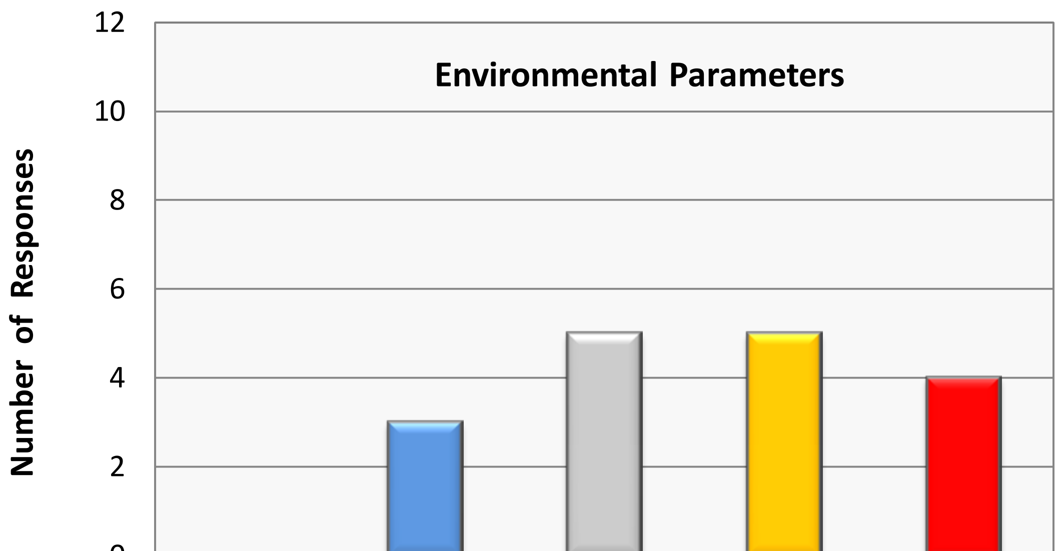
	Very low	Low	Medium	High	Very High
Number of Resp.	0	1	4	10	2
Percentage	0.0%	5.9%	23.5%	58.8%	11.8%

Figure 4.30. Given rates to economic parameters category by survey participants



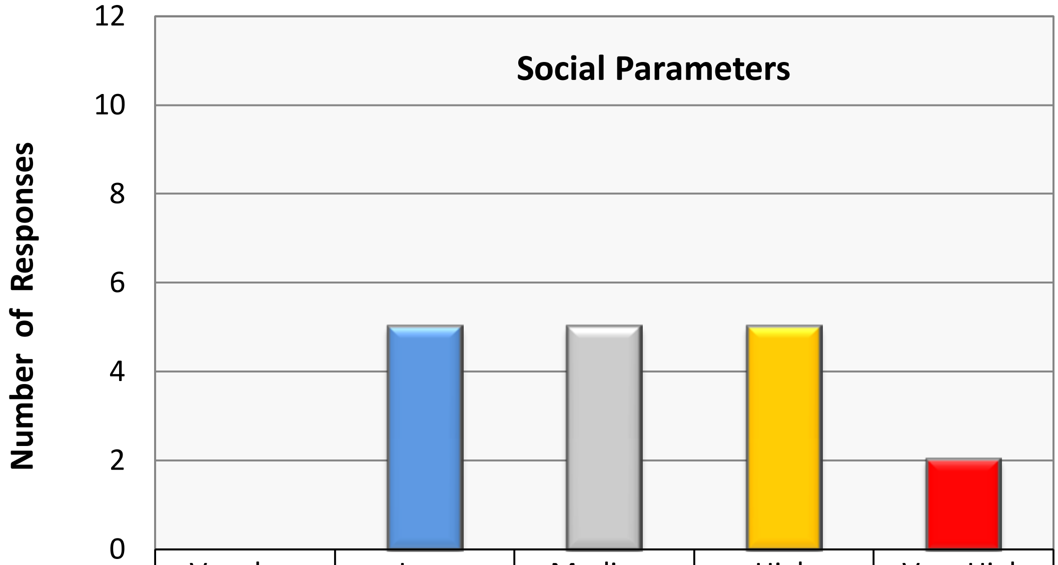
	Very low	Low	Medium	High	Very High
Number of Resp.	0	0	4	11	2
Percentage	0.0%	0.0%	23.5%	64.7%	11.8%

Figure 4.31. Given rates to financial parameters category by survey participants



	Very low	Low	Medium	High	Very High
Number of Resp.	0	3	5	5	4
Percentage	0.0%	17.6%	29.4%	29.4%	23.5%

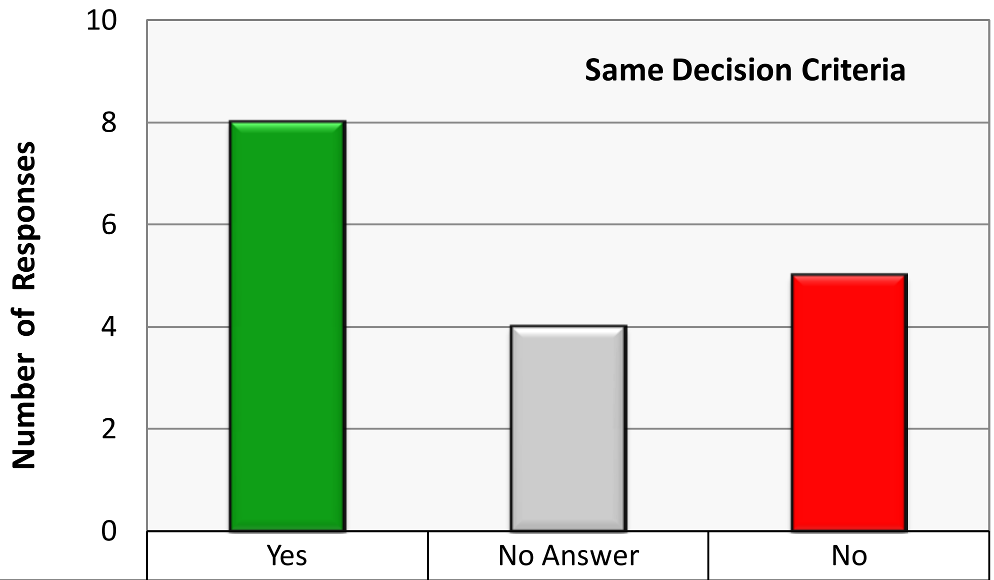
Figure 4.32. Given rates to environmental parameters category by survey participants



	Very low	Low	Medium	High	Very High
Number of Resp.	0	5	5	5	2
Percentage	0.0%	29.4%	29.4%	29.4%	11.8%

Figure 4.33. Given rates to social parameters category by survey participants

Question 14 emphasized the importance of evaluation and decision makings for different types of municipal infrastructure projects. This question asked respondents to specify whether their city believes that decision criteria for the selection of municipal infrastructure should be the same for different types of infrastructure. This question had three options: “Yes”, “No”, and “No Answer”. Fig. 4.34 shows the breakdown of respondents’ answers.



	Yes	No Answer	No
Number of Resp.	8	4	5
Percentage	47.1%	23.5%	29.4%

Figure 4.34. Survey respondents' agreement/ disagreement of same decision criteria for different type of infrastructure projects

4.4. Discussion of Survey Results

Each of the ratings of the decision criteria gives an interesting and unique glimpse into the various municipalities'' views of that criteria. Although it is difficult to summarize the results in a number of succinct comments, it is clearly visible that their absolute and relative rankings are extremely closely related. The results fall into two categories: a close matching of results or a distribution of results. For example, Fig. 4.3 relates to "Asset Condition" and it shows that all participants rated it as "High" or "Very High". Similarly, Fig. 4.27 relates to "Safety" and shows that all participants rated this as a significant decision criterion, with no exception. This holds true for a large portion of the decision criteria. And the reverse hold true for many decision criteria, such as in Fig. 4.26, as it relates to Geographic Distribution of Funding– this is NOT a significant decision criteria. The remaining decision criteria have a complete distribution of responses (Figs. 4.5, 4.6, 4.17, 4.19, 4.25) perhaps indicating that there is no consensus of opinion for that decision criteria or that the preference varies according the municipality.

On the other hand, regarding the categories of decision criteria (Figs. 4.29 to 4.34), it appears that Technical/Engineering Parameters, Economic Parameters and Financial Parameters have significant importance; whereas, the ratings of Environmental and Social Parameters is not consistent, at all.

A summary of assigned scores by respondents to all decision criteria and group decision criteria are listed in Table A.1.

4.5. Weight of Criteria

Using the method described in section 3.3.2 of this thesis, the weights of decision criterion have been computed using the result of the survey. As presented in Section 4.3, respondents rated the relative importance of each selected decision criteria. This was normalized using five linguistic fuzzy variables as mentioned in section 3.3. An arithmetic mean operation for fuzzy numbers has been applied to calculate the average fuzzy variable that shows the relative importance of each decision criteria within each category without considering the weight of the category of criteria. The same approach also has been applied to calculate the relative importance of each decision category. Figs. 4.35 to 4.39 illustrate the average fuzzy scores for the decision criteria obtained from the survey results without considering the assigned scores to the related category of criteria. Similarly, Fig. 4.40 shows the average fuzzy scores for the categories of decision criteria.

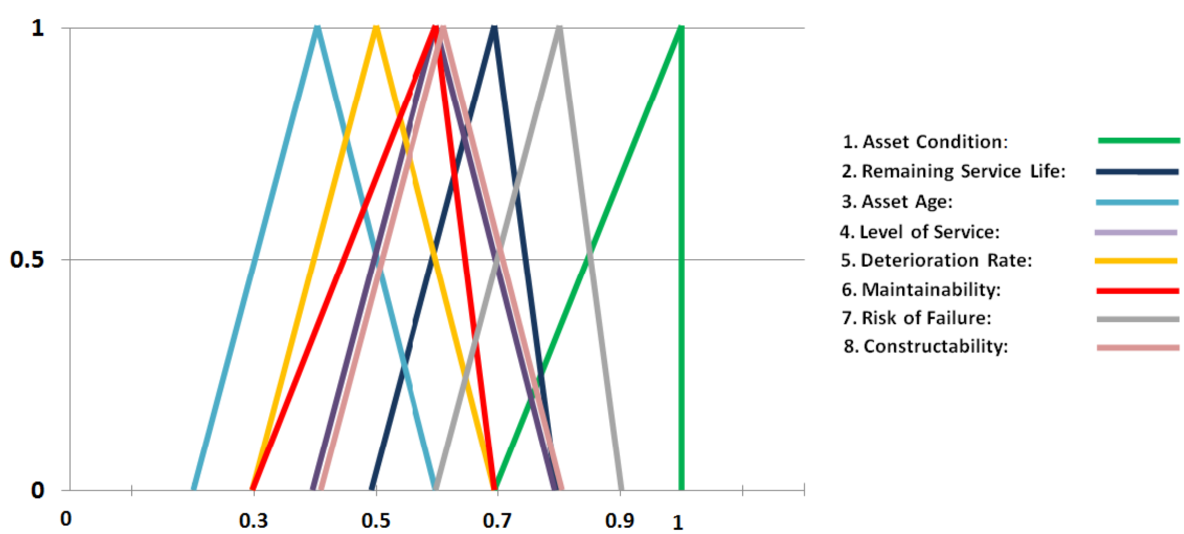


Figure 4.35. The average fuzzy score for technical and engineering criteria within relevant group

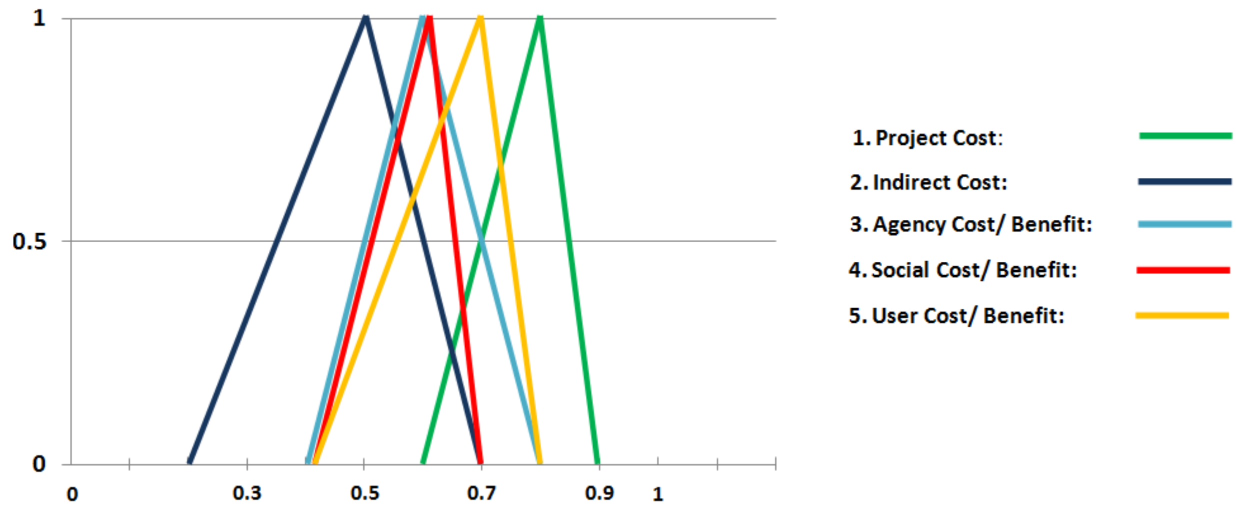


Figure 4.36. The average fuzzy score for economic criteria within relevant group

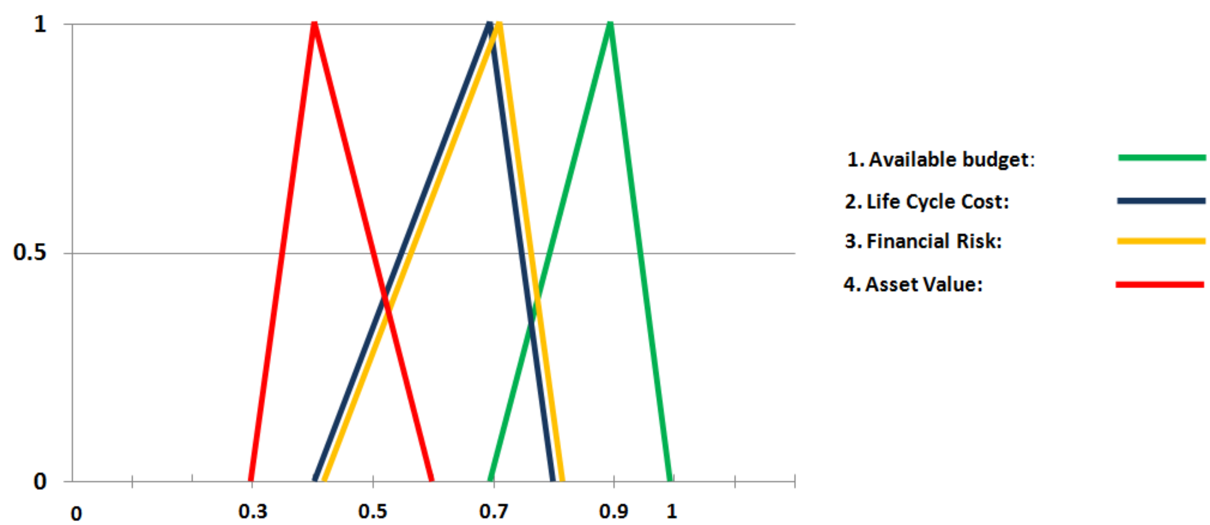


Figure 4.37. The average fuzzy score for financial criteria within relevant group

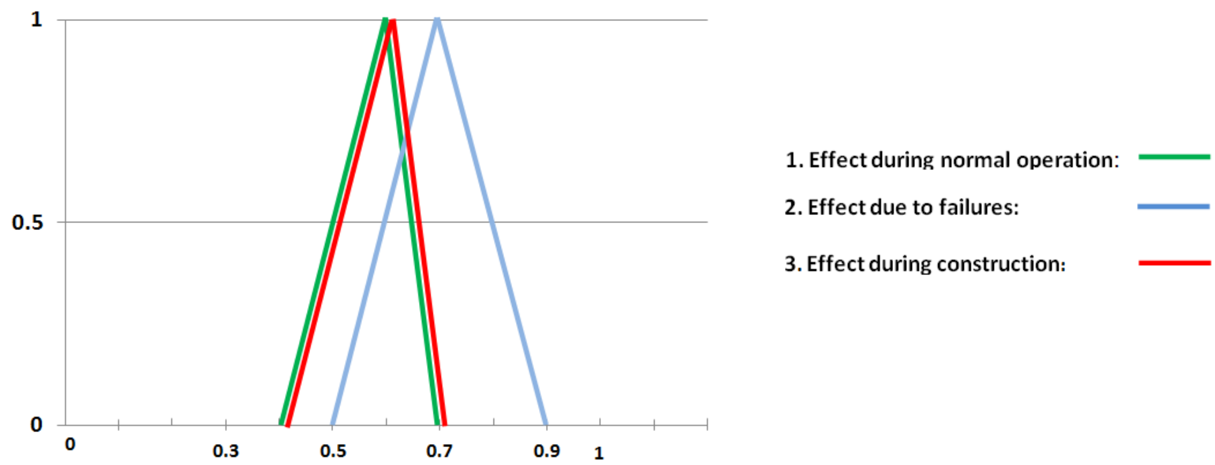


Figure 4.38. The average fuzzy score for environmental criteria within relevant group

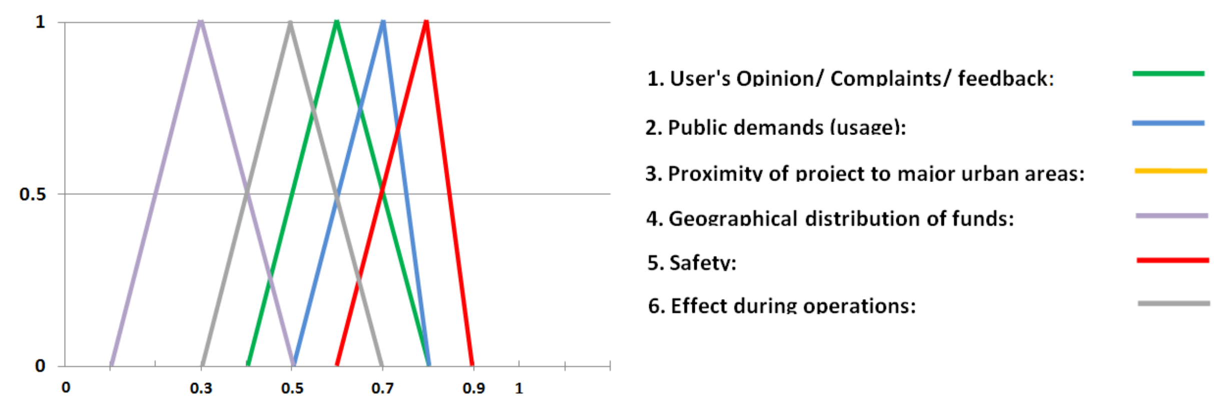


Figure 4.39. The average fuzzy score for social criteria within relevant group

Fig. 4.40 shows the average fuzzy variables for the general categories of decision criteria which is computed basis on the respondents' responses.

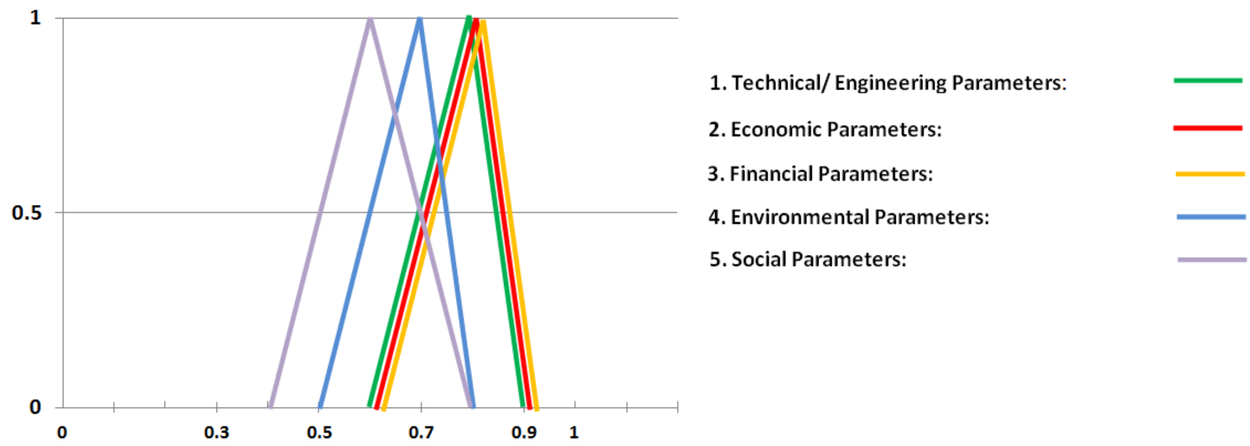


Figure 4.40. The average fuzzy score for each category of decision criteria

According to Section 3.3 of this thesis, the average fuzzy variables have been defuzzified (equation 3.7). The fuzzy variables which have been used for this study were already normalized. The average fuzzy numbers, defuzzified numbers, weights of the category of decision criteria are shown in Table 4.2.

Table 4.1 Average fuzzy scores, defuzzified scores, weights of the category of decision criteria

No.	Category	Average Fuzzy Score	Defuzzified Score	Weight
1	Technical/ Engineering Parameters	(0.6, 0.8, 0.9)	0.775	21.53%
2	Economic Parameters	(0.6, 0.8, 0.9)	0.775	21.53%
3	Financial Parameters	(0.6, 0.8, 0.9)	0.775	21.53%
4	Environmental Parameters	(0.5, 0.7, 0.8)	0.675	18.75%
5	Social Parameters	(0.4, 0.6, 0.8)	0.600	16.67%

Similarly, the average fuzzy scores, defuzzified scores, and weight of each decision criteria within the related category are summarized in Tables 4.3 to 4.7.

Table 4.2. Average fuzzy scores, defuzzified scores, weights of the category of technical and engineering criteria within related category

No.	Decision Criterion	Average fuzzy score within related category	Defuzzified score within related category	Weight within related category
1	Asset Condition	(0.70, 1.0, 1.0)	0.925	18.41%
2	Remaining Service Life	(0.5, 0.7, 0.8)	0.675	13.43%
3	Asset Age	(0.2, 0.4, 0.6)	0.400	7.96%
4	Level of Service	(0.4, 0.6, 0.8)	0.600	11.94%
5	Deterioration Rate	(0.3, 0.5, 0.7)	0.500	9.95%
6	Maintainability	(0.3, 0.6, 0.7)	0.550	10.95%
7	Risk of Failure	(0.6, 0.8, 0.9)	0.775	15.42%
8	Constructability	(0.4, 0.6, 0.8)	0.600	11.94%

Table 4.3. Average fuzzy scores, defuzzified scores, weights of the category of economic criteria within related category

No.	Decision Criterion	Average fuzzy score within related category	Defuzzified score within related category	Weight within related category
1	Project Cost	(0.6, 0.8, 0.9)	0.775	25.20%
2	Indirect Cost	(0.2, 0.5, 0.7)	0.475	15.45%
3	Agency Cost/ Benefit	(0.4, 0.6, 0.8)	0.600	19.51%
4	Social Cost/ Benefit	(0.4, 0.6, 0.7)	0.575	18.70%
5	User Cost/ Benefit	(0.4, 0.7, 0.8)	0.650	21.14%

Table 4.4. Average fuzzy scores, defuzzified scores, weights of the category of financial criteria within related category

No.	Decision Criterion	Average fuzzy score within related category	Defuzzified score within related category	Weight within related category
1	Available budget	(0.7, 0.9, 1.0)	0.875	32.41%
2	Life Cycle Cost	(0.4, 0.7, 0.8)	0.650	27.78%
3	Financial Risk	(0.4, 0.7, 0.8)	0.650	24.07%
4	Asset Value	(0.3, 0.4, 0.6)	0.425	15.74%

Table 4.5. Average fuzzy scores, defuzzified scores, weights of the category of environmental criteria within related category

No.	Decision Criterion	Average fuzzy score within related category	Defuzzified score within related category	Weight within related category
1	Effect during normal operation	(0.4, 0.6, 0.7)	0.575	29.48%
2	Effect due to failures	(0.5, 0.7, 0.9)	0.700	35.89%
3	Effect during construction	(0.4, 0.6, 0.7)	0.675	34.63%

Table 4.6. Average fuzzy scores, defuzzified scores, weights of the category of social criteria within related category

No.	Decision Criterion	Average fuzzy score within related category	Defuzzified score within related category	Weight within related category
1	User's Opinion/ Complaints/ feedback	(0.4, 0.6, 0.8)	0.600	18.46%
2	Public demands (usage)	(0.5, 0.7, 0.8)	0.675	20.77%
3	Proximity of project to major urban areas	(0.2, 0.4, 0.6)	0.400	12.31%
4	Geographical distribution of funds	(0.1, 0.3, 0.5)	0.300	9.23%
5	Safety	(0.6, 0.8, 0.90)	0.775	23.85%
6	Effect during operations	(0.3, 0.5, 0.7)	0.500	15.38%

The overall fuzzy and defuzzified score as well as the overall weight of each decision criteria are summarized in Tables 4.8. The Hierarchical Approach, as described in section 3.3.2, is used to calculate the overall weight of decision criteria. It should be noted that in Table 4.8 the overall fuzzy scores are normalized and they can be assumed as fuzzy weights.

Table 4.7 Overall fuzzy and defuzzified scores, overall weights of the criteria

No.	Decision Criterion	Overall fuzzy score	Overall defuzzified score	Overall weight	Overall Ranking
1	Asset Condition	(0.42, 0.79, 0.93)	0.736	5.99%	1
2	Available budget	(0.41, 0.76, 0.91)	0.709	5.78%	2
3	Project Cost	(0.33, 0.63, 0.83)	0.605	4.93%	3
4	Risk of Failure	(0.33, 0.62, 0.82)	0.597	4.86%	4
5	Remaining Service Life	(0.30, 0.58, 0.78)	0.557	4.54%	5
6	Life Cycle Cost	(0.28, 0.57, 0.76)	0.546	4.45%	6
7	Financial Risk	(0.29, 0.56, 0.76)	0.541	4.41%	7
8	Effect due to failures	(0.28, 0.56, 0.73)	0.533	4.34%	8
9	User Cost/ Benefit	(0.28, 0.54, 0.74)	0.528	4.30%	9
10	Agency Cost/ Benefit	(0.26, 0.52, 0.72)	0.505	4.11%	10
11	Safety	(0.22, 0.52, 0.71)	0.495	4.03%	11
12	Constructability	(0.25, 0.50, 0.69)	0.483	3.93%	12
13	Level of Service	(0.23, 0.48, 0.70)	0.473	3.85%	13
14	Maintainability	(0.21, 0.48, 0.69)	0.461	3.75%	14
15	Social Cost/ Benefit	(0.22, 0.46, 0.67)	0.452	3.68%	15
16	Effect during construction	(0.21, 0.44, 0.64)	0.433	3.53%	16
17	Effect during normal operation	(0.20, 0.44, 0.63)	0.429	3.50%	17
18	Public demands (usage)	(0.19, 0.43, 0.65)	0.425	3.46%	18
19	Deterioration Rate	(0.17, 0.41, 0.64)	0.406	3.31%	19
20	User's Opinion/ Complaints/ feedback	(0.17, 0.41, 0.62)	0.403	3.28%	20
21	Asset Value	(0.15, 0.36, 0.59)	0.366	2.98%	21
22	Asset Age	(0.14, 0.36, 0.58)	0.360	2.93%	22
23	Effect during operations (from social aspect)	(0.16, 0.36, 0.54)	0.356	2.90%	23
24	Indirect Cost	(0.13, 0.35, 0.58)	0.356	2.90%	23
25	Proximity of project to major urban areas	(0.12, 0.31, 0.51)	0.312	2.54%	24
26	Geographical distribution of funds	(0.05, 0.20, 0.39)	0.210	1.71%	25

4.6. Numerical Example

Through the previous sections, a list of most important decision criteria for evaluation of municipal infrastructure is provided. Then, the survey was conducted among large number Canadian municipalities to calculate the municipalities' preferences in order to compute the relative importance of each decision criterion. Now in this section a numerical example is designed to demonstrate how the proposed method in chapter 3, Hybrid Fuzzy AHP-TOPSIS, works and is able to provide an outranking of municipal infrastructure projects.

For that purpose, assume that a group of asset managers including three experts want to provide an action plan of some complex and relatively large scale municipal infrastructure projects for next few years. There are the usual constraints such as limited budget, limited equipment, lack of a skilled workforce, and so on. In order to deal with the existing constraints and to efficiently use the existing resources, these three experts decided to perform an assessment and to prioritize the projects. In this example, it is shown that they can evaluate the projects effectively and can jointly consider financial, economic, environment, social, and engineering/ technical aspects of the individual projects.

Now, assume that they used the decision criteria (Table 3.1) and fuzzy linguistic evaluation scale for the alternative (Table 3.3) provided in this thesis. Table 4.9 summarizes the experts' opinions about these four projects. In Table 4.9, $\tilde{x}_{ij}$ indicates the fuzzy linguistic rating of alternative A_j with respect to criterion C_i. Additionally, $\tilde{x}_{ij}$; $0 > j \geq 4$ is related to decision maker No. 1 and $\tilde{x}_{ij}$; $4 > j \geq 8$ is related to decision maker No. 2. Similarly, $\tilde{x}_{ij}$; $8 > j \geq 12$ is related to the decision maker No. 3.

Table 4.8. The fuzzy evaluation table of four alternatives under group decision making

		Expert 1				Expert 2				Expert 3			
No	**Decision Criterion**	**P.1**	**P.2**	**P.3**	**P.4**	**P.1**	**P.2**	**P.3**	**P.4**	**P.1**	**P.2**	**P.3**	**P.4**
1	Asset Condition	L	F	H	F	VL	ML	H	MH	ML	F	MH	F
2	Remaining Service	F	F	MH	ML	L	L	MH	F	VL	L	F	ML
3	Asset Age	H	MH	ML	MH	VH	H	L	H	VH	H	F	F
4	Level of Service	L	ML	MH	F	VL	L	F	L	L	ML	F	L
5	Deterioration Rate	H	MH	L	MH	H	F	VL	ML	MH	F	L	F
6	Maintainability	ML	F	L	MH	F	ML	VL	VL	F	MH	ML	F
7	Risk of Failure	H	MH	ML	F	MH	F	VL	ML	F	MH	MH	ML
8	Constructability	ML	ML	VL	H	F	MH	L	MH	F	MH	VL	H
9	Project Cost	H	MH	F	ML	MH	F	ML	ML	H	MH	VL	ML
10	Indirect Cost	L	ML	F	ML	L	F	ML	F	L	F	ML	F
11	Agency Cost/ Benefit	VL	L	MH	ML	VL	F	MH	F	L	ML	H	ML
12	Social Cost/ Benefit	ML	F	F	MH	L	F	F	H	L	F	F	MH
13	User Cost/ Benefit	L	ML	F	F	ML	F	F	MH	VL	F	ML	H
14	Available budget	MH	F	ML	L	F	F	ML	F	F	ML	H	MH
15	Life Cycle Cost	MH	MH	VH	VH	F	H	MH	F	MH	F	F	F
16	Financial Risk	ML	F	MH	L	L	MH	H	VL	F	MH	H	ML
17	Asset Value	H	MH	F	MH	F	VH	F	H	MH	F	F	F
18	Effect during normal operation	F	ML	VL	MH	VH	H	F	F	L	F	L	MH
19	Effect due to failures	H	MH	F	F	MH	L	ML	MH	F	L	MH	H
20	Effect during construction	MH	F	F	H	MH	F	L	F	H	MH	MH	MH
21	User's Opinion/ Complaints/ feedback	H	F	VL	ML	MH	H	ML	L	F	F	ML	L
22	Public demands	MH	F	F	ML	F	ML	MH	H	F	ML	L	ML
23	Proximity of project to major urban areas	ML	F	VL	MH	F	L	F	H	MH	F	VL	VH
24	Geographical distribution of funds	VH	H	VL	L	H	F	ML	F	F	F	F	F
25	Safety	L	L	F	F	ML	MH	F	L	ML	H	H	ML
26	Effect during operations (from social aspect)	H	F	F	H	ML	F	ML	H	VH	MH	F	ML

At this stage, according to equation 3.14, the average fuzzy variable of experts' opinions is computed as shown in Table 4.10.

Table 4.9. Average fuzzy performance rate of alternative

No.	Decision Criterion	P.1	P.2	P.3	P.4
1	Asset Condition	(1.3, 2, 3.3)	(2.7, 4.3, 6.3)	(6.3, 8.3, 9.7)	(3.7, 5.7, 7.7)
2	Remaining Service Life	(1.7, 2.7, 4)	(1.7, 3, 4.3)	(4.3, 6.3, 8.3)	(2.3, 3.7, 5.7)
3	Asset Age	(8.3, 9.7, 10)	(6.3, 8.3, 9.7)	(2, 3.3, 5)	(5, 7, 8.7)
4	Level of Service	(1, 1.7, 2.7)	(1.7, 2.7, 4.3)	(3.7, 5.7, 7.7)	(1.7, 3, 4.3)
5	Deterioration Rate	(6.3, 8.3, 9.7)	(3.7, 5.7, 7.7)	(1, 1.7, 2.7)	(3.3, 5, 7)
6	Maintainability	(2.7, 4.3, 6.3)	(3.3, 5, 7)	(1.3, 2, 3.3)	(3, 4.3, 6)
7	Risk of Failure	(5, 7, 8.7)	(4.3, 6.3, 8.3)	(2.7, 3.7, 5.3)	(2.3, 3.7, 5.7)
8	Constructability	(2.7, 4.3, 6.3)	(4, 5.7, 7.7)	(1, 1.3, 2.3)	(6.3, 8.3, 9.7)
9	Project Cost	(6.3, 8.3, 9.7)	(4.3, 6.3, 8.3)	(2, 3, 4.7)	(2, 3, 5)
10	Indirect Cost	(1, 2, 3)	(2.7, 4.3, 6.3)	(2.3, 3.7, 5.7)	(2.7, 4.3, 6.3)
11	Agency Cost/ Benefit	(1, 1.3, 2.3)	(2, 3.3, 5)	(5.7, 7.7, 9.3)	(2.3, 3.7, 5.7)
12	Social Cost/ Benefit	(1.3, 2.3, 3.7)	(3, 5, 7)	(3, 5, 7)	(5.7, 7.7, 9.3)
13	User Cost/ Benefit	(1.3, 2, 3.3)	(2.7, 4.3, 6.3)	(2.7, 4.3, 6.3)	(5, 7, 8.7)
14	Available budget	(3.7, 5.7, 7.7)	(2.7, 4.3, 6.3)	(3.7, 5, 6.7)	(3.7, 5.7, 7.7)
15	Life Cycle Cost	(4.3, 6.3, 8.3)	(5, 7, 8.7)	(5.7, 7.3, 8.7)	(5, 6.7, 8)
16	Financial Risk	(2, 3.3, 5)	(4.3, 6.3, 8.3)	(6.3, 8.3, 9.7)	(1.3, 2, 3.3)
17	Asset Value	(5, 7, 8.7)	(5.7, 7.3, 8.7)	(3, 5, 7)	(5, 7, 8.7)
18	Effect during normal operation	(4.3, 5.7, 6.7)	(4, 5.7, 7.3)	(1.7, 2.7, 4)	(4.3, 6.3, 8.3)
19	Effect due to failures	(5, 7, 8.7)	(2.3, 3.7, 5)	(3.3, 5, 7)	(5, 7, 8.7)
20	Effect during construction	(5.7, 7.7, 9.3)	(3.7, 5.7, 7.7)	(3, 4.7, 6.3)	(5, 7, 8.7)
21	User's Opinion/ Complaints/ feedback	(5, 7, 8.7)	(4.3, 6.3, 8)	(1.7, 2.3, 4)	(1.3, 2.3, 3.7)
22	Public demands (usage)	(3.7, 5.7, 7.7)	(2.3, 3.7, 5.7)	(3, 4.7, 6.3)	(3.7, 5, 6.7)
23	Proximity of project to major urban areas	(3.3, 5, 7)	(2.3, 4, 5.7)	(1.7, 2.3, 3.7)	(7, 8.7, 9.7)
24	Geographical distribution of funds	(6.3, 8, 9)	(4.3, 6.3, 8)	(2, 3, 4.7)	(2.3, 4, 5.7)
25	Safety	(1.7, 2.7, 4.3)	(4.3, 6, 7.3)	(4.3, 6.3, 8)	(2, 3.3, 5)
26	Effect during operations (from social aspect)	(6, 7.3, 8.)	(3.7, 5.7, 7.7)	(2.7, 4.3, 6.3)	(5.3, 7, 8.3)

At this step, the average fuzzy performance ratings of alternatives are normalized according to equations 3.16 to 3.19. These normalized fuzzy performance rates are listed in Table 4.11.

Table 4.10. Normalized fuzzy performance rate of four alternative

No.	Decision Criterion	P.1	P.2	P.3	P.4
1	Asset Condition	(0.13, 0.2, 0.33)	(0.28, 0.45, 0.66)	(0.66, 0.86, 1)	(0.38, 0.59, 0.79)
2	Remaining Service Life	(0.17, 0.27, 0.4)	(0.17, 0.31, 0.45)	(0.45, 0.66, 0.86)	(0.24, 0.38, 0.59)
3	Asset Age	(0.83, 0.97, 1)	(0.66, 0.86, 1)	(0.21, 0.34, 0.52)	(0.52, 0.72, 0.9)
4	Level of Service	(0.1, 0.17, 0.27)	(0.17, 0.28, 0.45)	(0.38, 0.59, 0.79)	(0.17, 0.31, 0.45)
5	Deterioration Rate	(0.1, 0.12, 0.16)	(0.26, 0.35, 0.55)	(0.38, 0.6, 1)	(0.19, 0.27, 0.4)
6	Maintainability	(0.27, 0.43, 0.63)	(0.34, 0.52, 0.72)	(0.14, 0.21, 0.34)	(0.31, 0.45, 0.62)
7	Risk of Failure	(0.12, 0.14, 0.2)	(0.24, 0.32, 0.46)	(0.19, 0.27, 0.38)	(0.24, 0.36, 0.57)
8	Constructability	(0.27, 0.43, 0.63)	(0.41, 0.59, 0.79)	(0.1, 0.14, 0.24)	(0.66, 0.86, 1)
9	Project Cost	(0.1, 0.12, 0.16)	(0.24, 0.32, 0.46)	(0.21, 0.33, 0.5)	(0.27, 0.44, 0.67)
10	Indirect Cost	(0.33, 0.5, 1)	(0.32, 0.46, 0.75)	(0.18, 0.27, 0.43)	(0.21, 0.31, 0.5)
11	Agency Cost/ Benefit	(0.43, 0.75, 1)	(0.4, 0.6, 1)	(0.11, 0.13, 0.18)	(0.24, 0.36, 0.57)
12	Social Cost/ Benefit	(0.27, 0.43, 0.75)	(0.29, 0.4, 0.67)	(0.14, 0.2, 0.33)	(0.14, 0.17, 0.24)
13	User Cost/ Benefit	(0.3, 0.5, 0.75)	(0.32, 0.46, 0.75)	(0.16, 0.23, 0.38)	(0.15, 0.19, 0.27)
14	Available budget	(0.37, 0.57, 0.77)	(0.28, 0.45, 0.66)	(0.38, 0.52, 0.69)	(0.38, 0.59, 0.79)
15	Life Cycle Cost	(0.12, 0.16, 0.23)	(0.23, 0.29, 0.4)	(0.12, 0.14, 0.18)	(0.17, 0.2, 0.27)
16	Financial Risk	(0.2, 0.3, 0.5)	(0.24, 0.32, 0.46)	(0.1, 0.12, 0.16)	(0.4, 0.67, 1)
17	Asset Value	(0.5, 0.7, 0.87)	(0.59, 0.76, 0.9)	(0.31, 0.52, 0.72)	(0.52, 0.72, 0.9)
18	Effect during normal operation	(0.15, 0.18, 0.23)	(0.27, 0.35, 0.5)	(0.25, 0.38, 0.6)	(0.16, 0.21, 0.31)
19	Effect due to failures	(0.12, 0.14, 0.2)	(0.4, 0.55, 0.86)	(0.14, 0.2, 0.3)	(0.15, 0.19, 0.27)
20	Effect during construction	(0.11, 0.13, 0.18)	(0.26, 0.35, 0.55)	(0.16, 0.21, 0.33)	(0.15, 0.19, 0.27)
21	User's Opinion/ Complaints/ feedback	(0.12, 0.14, 0.2)	(0.25, 0.32, 0.46)	(0.25, 0.43, 0.6)	(0.36, 0.57, 1)
22	Public demands (usage)	(0.37, 0.57, 0.77)	(0.24, 0.38, 0.59)	(0.31, 0.48, 0.66)	(0.38, 0.52, 0.69)
23	Proximity of project to major urban areas	(0.33, 0.5, 0.7)	(0.24, 0.41, 0.59)	(0.17, 0.24, 0.38)	(0.72, 0.9, 1)
24	Geographical distribution of funds	(0.63, 0.8, 0.9)	(0.45, 0.66, 0.83)	(0.21, 0.31, 0.48)	(0.24, 0.41, 0.59)
25	Safety	(0.17, 0.27, 0.43)	(0.45, 0.62, 0.76)	(0.45, 0.66, 0.83)	(0.21, 0.34, 0.52)
26	Effect during operations (from social aspect)	(0.12, 0.14, 0.17)	(0.26, 0.35, 0.55)	(0.16, 0.23, 0.38)	(0.16, 0.19, 0.25)

Now, the calculated weight of criteria are employed and multiplied with the normalized fuzzy performance rate from Table 4.11. These fuzzy weighted normalized evaluation matrixes of four projects are listed in Table 4.12.

Table 4.11. Weighted normalized evaluation matrix of four alternatives

No.	Decision Criterion	P.1	P.2	P.3	P.4
1	Asset Condition	(0.06, 0.16, 0.31)	(0.12, 0.36, 0.61)	(0.28, 0.69, 0.93)	(0.16, 0.47, 0.74)
2	Remaining Service Life	(0.05, 0.15, 0.31)	(0.05, 0.18, 0.35)	(0.13, 0.38, 0.67)	(0.07, 0.22, 0.45)
3	Asset Age	(0.12, 0.35, 0.58)	(0.09, 0.31, 0.58)	(0.03, 0.12, 0.30)	(0.07, 0.26, 0.52)
4	Level of Service	(0.02, 0.08, 0.19)	(0.04, 0.13, 0.31)	(0.09, 0.28, 0.56)	(0.04, 0.15, 0.31)
5	Deterioration Rate	(0.02, 0.05, 0.10)	(0.04, 0.14, 0.35)	(0.06, 0.25, 0.64)	(0.03, 0.11, 0.26)
6	Maintainability	(0.05, 0.21, 0.43)	(0.07, 0.34, 0.50)	(0.03, 0.10, 0.24)	(0.06, 0.21, 0.43)
7	Risk of Failure	(0.04, 0.09, 0.16)	(0.08, 0.20, 0.38)	(0.06, 0.17, 0.31)	(0.08, 0.23, 0.47)
8	Constructability	(0.07, 0.21, 0.44)	(0.10, 0.29, 0.55)	(0.03, 0.07, 0.17)	(0.16, 0.43, 0.69)
9	Project Cost	(0.03, 0.08, 0.13)	(0.08, 0.20, 0.38)	(0.07, 0.21, 0.41)	(0.09, 0.28, 0.55)
10	Indirect Cost	(0.04, 0.18, 0.58)	(0.04, 0.16, 0.44)	(0.02, 0.10, 0.25)	(0.03, 0.11, 0.29)
11	Agency Cost/ Benefit	(0.11, 0.39, 0.72)	(0.10, 0.31, 0.72)	(0.03, 0.07, 0.13)	(0.06, 0.19, 0.41)
12	Social Cost/ Benefit	(0.06, 0.20, 0.50)	(0.06, 0.18, 0.45)	(0.03, 0.09, 0.22)	(0.03, 0.08, 0.16)
13	User Cost/ Benefit	(0.08, 0.27, 0.56)	(0.09, 0.25, 0.56)	(0.04, 0.13, 0.28)	(0.04, 0.10, 0.20)
14	Available budget	(0.15, 0.43, 0.70)	(0.11, 0.34, 0.60)	(0.15, 0.39, 0.63)	(0.15, 0.44, 0.72)
15	Life Cycle Cost	(0.03, 0.09, 0.18)	(0.06, 0.16, 0.30)	(0.03, 0.08, 0.13)	(0.05, 0.11, 0.20)
16	Financial Risk	(0.06, 0.17, 0.38)	(0.07, 0.18, 0.35)	(0.03, 0.07, 0.12)	(0.11, 0.37, 0.76)
17	Asset Value	(0.08, 0.25, 0.51)	(0.09, 0.27, 0.53)	(0.05, 0.19, 0.43)	(0.08, 0.26, 0.53)
18	Effect during normal operation	(0.03, 0.08, 0.15)	(0.05, 0.16, 0.32)	(0.05, 0.17, 0.38)	(0.03, 0.09, 0.20)
19	Effect due to failures	(0.03, 0.08, 0.15)	(0.11, 0.31, 0.62)	(0.04, 0.11, 0.22)	(0.04, 0.11, 0.19)
20	Effect during construction	(0.02, 0.06, 0.11)	(0.05, 0.16, 0.35)	(0.03, 0.09, 0.21)	(0.03, 0.08, 0.17)
21	User's Opinion/ Complaints/ feedback	(0.02, 0.06, 0.12)	(0.04, 0.13, 0.29)	(0.05, 0.18, 0.37)	(0.06, 0.23, 0.62)
22	Public demands (usage)	(0.07, 0.24, 0.50)	(0.05, 0.16, 0.38)	(0.06, 0.21, 0.42)	(0.07, 0.22, 0.45)
23	Proximity of project to major urban areas	(0.04, 0.16, 0.36)	(0.03, 0.13, 0.30)	(0.02, 0.07, 0.19)	(0.08, 0.28, 0.51)
24	Geographical distribution of funds	(0.03, 0.16, 0.36)	(0.02, 0.13, 0.33)	(0.01, 0.06, 0.19)	(0.01, 0.08, 0.23)
25	Safety	(0.04, 0.14, 0.31)	(0.10, 0.32, 0.54)	(0.10, 0.34, 0.59)	(0.05, 0.18, 0.37)
26	Effect during operations (from social aspect)	(0.02, 0.05, 0.09)	(0.04, 0.13, 0.30)	(0.03, 0.08, 0.20)	(0.03, 0.07, 0.14)

According to equations 3.24 and 3.25, the distance of each project from fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS) are computed in this step. It should be noted for this numerical example, equations 3.22 and 3.23 are used to calculate FPIS and FNIS. Additionally, in this thesis, equation 2.25 is applied to compute the distance between two fuzzy numbers with triangular membership function. Table 4.13 shows the distances of each alternative from FNIS and PNIS for each criterion.

Table 4.12. The distance measurement of alternatives from FPIS and FNIS

No.	Decision Criterion	P.1		P.2		P.3		P.4	
		d^+	d^-	d^+	d^-	d^+	d^-	d^+	d^-
1	Asset Condition	0.831	0.204	0.670	0.413	0.457	0.686	0.594	0.512
2	Remaining Service Life	0.836	0.202	0.816	0.228	0.645	0.450	0.768	0.294
3	Asset Age	0.679	0.397	0.702	0.384	0.856	0.188	0.739	0.339
4	Level of Service	0.906	0.118	0.846	0.198	0.718	0.363	0.840	0.202
5	Deterioration Rate	0.945	0.066	0.831	0.220	0.725	0.397	0.873	0.162
6	Maintainability	0.784	0.280	0.749	0.323	0.883	0.149	0.780	0.277
7	Risk of Failure	0.905	0.110	0.792	0.250	0.827	0.205	0.760	0.303
8	Constructability	0.776	0.285	0.710	0.364	0.915	0.105	0.613	0.479
9	Project Cost	0.921	0.090	0.790	0.253	0.781	0.272	0.719	0.362
10	Indirect Cost	0.767	0.354	0.803	0.271	0.882	0.156	0.864	0.181
11	Agency Cost/ Benefit	0.643	0.476	0.672	0.455	0.927	0.084	0.793	0.263
12	Social Cost/ Benefit	0.770	0.313	0.786	0.281	0.888	0.140	0.912	0.104
13	User Cost/ Benefit	0.722	0.362	0.727	0.357	0.856	0.178	0.887	0.132
14	Available budget	0.616	0.482	0.680	0.402	0.638	0.437	0.605	0.498
15	Life Cycle Cost	0.902	0.116	0.829	0.203	0.919	0.092	0.881	0.137
16	Financial Risk	0.809	0.243	0.809	0.231	0.928	0.081	0.642	0.495
17	Asset Value	0.742	0.332	0.725	0.347	0.795	0.270	0.734	0.343
18	Effect during normal operation	0.916	0.097	0.831	0.207	0.813	0.241	0.896	0.126
19	Effect due to failures	0.915	0.098	0.686	0.406	0.880	0.143	0.888	0.130
20	Effect during construction	0.937	0.074	0.823	0.222	0.890	0.136	0.906	0.111
21	User's Opinion/ Complaints/ feedback	0.934	0.080	0.853	0.183	0.815	0.238	0.733	0.383
22	Public demands (usage)	0.751	0.321	0.816	0.240	0.784	0.275	0.769	0.291
23	Proximity of project to major urban areas	0.827	0.226	0.856	0.188	0.907	0.120	0.730	0.339
24	Geographical distribution of funds	0.829	0.225	0.850	0.203	0.916	0.116	0.896	0.142
25	Safety	0.846	0.196	0.702	0.367	0.686	0.396	0.813	0.237
26	Effect during operations (from social aspect)	0.948	0.060	0.852	0.187	0.899	0.128	0.925	0.089

As the last step, the total distance and close coefficient (see equation 3.26) of the four projects are computed and listed in Table 4.14. As shown before in step 8 of Fig. 2.14, the alternative with higher value of close coefficient is desirable. In the end, based on the obtained close coefficients of alternatives, the preference order of four project is P.2> P.4> P.3> P.1.

Table 4.13. Close coefficient and ranking of alternatives

	d^{+}	d^{-}	CC	**Ranking**
P.1	21.46	5.80	0.213	4
P.2	20.21	7.38	0.268	1
P.3	21.23	6.05	0.222	3
P.4	20.56	6.93	0.252	2

Chapter 5 Conclusion

This research study was developed to provide a decision making method to evaluate effectively and efficiently alternatives for municipal infrastructure projects. The method proposed for decision making is able to assist decision making for many types of asset managers and for any similar type of public or private organizations that need to evaluate projects and to make decisions about infrastructure type projects. The proposed decision making method, in fact, is a combination of existing classic multi criteria decision methods that suits the needs of these types of projects. Additionally, the proposed method was significantly modified to meet the main identified requirements in the domain and to address global issues regarding the state of the world's infrastructure assets.

The following procedure summarizes, in terms of some major milestones, how this research effort was developed, what main tasks and objectives were addressed, and what are the results.

Stage 1. As the first stage, the concept of asset management and definitions of infrastructure terms were reviewed. Definitions of asset management and of infrastructure, developed by public and private American, Canadian, Australian, and UK organizations are presented in sections 2.1, 2.2, and 2.3. These definitions and concepts give concise and precise ideas to the readers about the state of practice in the world regarding this domain; these also can be used by others interested in research in this domain or others working in the asset management arena.

Stage 2. Comprehensive literature reviews and research group discussions were conducted to provide answers to the main questions regarding decision making. Some main questions include: what decision making method is the most appropriate considering the scope of the research, who are the future users, what do these users commonly require and what is their average level of knowledge. Owing to the nature of asset management process and decision making of large scale infrastructure projects, as presented in section 2.4, Multi Criteria Decision Making (MCDM) methods were selected as a suitable candidate. Reasons for this selection were that MCDM is capable of dealing with conflicting criteria, it is straightforward to implement and it increases the users' reliability. Additionally, a general framework for the selection of a Decision Making/Aid Method is presented that outline the three main phases: Problem Acquisition, Problem Formulation, and Problem Solution. A review of major types of MCDM methods is presented that considers their strengths, weaknesses and applications: a hybrid method using AHP and TOPSIS was selected as a suitable candidate. At this stage, after reviewing the literature in this arena, this research identified that TOPSIS, as the core of a decision making method, has many important advantages. Some of the benefits are listed as follows:

(a) This method provides a sound logic which demonstrates the rationale of human choice;

(b) Abilities and advantages of TOPSIS turn it into an effective decision aid tool in group decision making environment;

(c) Cumbersome pairwise comparisons among alternatives of decision problem, such as in AHP, are not necessary for TOPSIS;

(d) Due to its meaningful and illustrative indices, TOPSIS is a suitable method for dealing with uncertain and fuzzy decision making environment.

Stage 3. In this stage, this research determined how this decision making method can consider and deal with many of the unique characteristics of decision making. For that purpose, after consultation with the asset management group of the City of Vancouver, as well as reviewing the relevant literature, this research identified some main issues regarding the practical aspects of decision making for complex infrastructure projects. The significant issues in practice include: incomplete information, non-obtainable information, unquantifiable information, and partial ignorance. They all are results of uncertain and ambiguous environment of decision making. As presented in section 2.6, this research selected fuzzy set theory as the most effective and most appropriate solution to deal with inherent uncertainties in decision making problem.

Stage 4. Identification of a series of effective and appropriate decision criteria was the main objective of this stage. As a matter of fact, all MCDM methods require a series of decision criteria upon which they can evaluate the alternatives. After reviewing the literature and research findings, it was decided that it was necessary to find a process or method to consider the full evaluation of decision criteria pertaining to municipal infrastructure. For that reason, this thesis added three groups of criteria in addition to the technical/ engineering parameters and financial parameters. Those three groups namely are: “Economic Parameters”, “Environmental Parameters”, and “Social Parameters”. A list of all decision criteria which are identified and applied in this research study is included in the thesis.

Stage 5. This research also attempted to consider the opinions of municipal asset managers and the preferences of specific municipalities and to suggest changes in decision making method accordingly. For that purpose, 17 questions were developed to query municipalities about their preference regarding decision criteria, which was followed by a survey that was conducted among some representatives from a large number of Canadian municipalities. After receiving the submitted responses, an analysis process was performed to examine the results. This analysis identified a number of interesting findings which are listed below:

1. This research findings show that financial parameters, economic parameters, and technical/engineering parameters are relatively more important than environmental parameters and social parameters, based on the preferences from the Canadian municipalities.

2. Asset condition, remaining service life, and risk of failure are the most important engineering and technical criteria. From another aspect, asset age and deterioration rate are the least important factors in this group.

3. Within the economic group, project cost is the most important factor while the indirect cost is the least significant one. In this group, based on submitted results, social cost/ benefit and agency cost/ benefit approximately have the same level of importance.

4. From a financial view, available budget is more important than life cycle cost and financial risk. Moreover, the asset value is less than other factors in this group.

5. Effect due to failure is more important than effect during construction and normal operation.

6. Safety and public demand are found as the most important criteria within social criteria category while the geographical distribution of funds is the least important one.

7. From overall approach among all categories of decision criteria, asset condition, available budget, project cost, risk of failure, and remaining service life are the most important decision criteria. The life cycle cost, financial risk, and effect due to the failure are decision criteria with less importance.

8. This study also showed that Canadian municipalities are willing to use the same decision criteria for different class of assets.

9. The responses received from the survey, in some cases, vary significantly from one municipality to another. It indicates that the asset managers in Canadian municipalities are not currently following consistent trends or guidelines in order to evaluate the infrastructure projects.

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Appendix A: Questions of The Survey

Evaluation and Selection of Municipal Infrastructure Projects

1) First name and last name:

____

2) Current Organization / Institution:

____

3) Current Position:

____

4) Years of Technical Related Experience:

____

5) Note: the rest of the questions will all deal with the criteria used for selecting which infrastructure projects will be given priority

❍ Ok

6) Please rate the following technical and engineering decision criteria in terms of their relative importance for selection of municipal infrastructure projects:

	Not Considered	Very low	Low	Medium	High	Very High
Asset Condition	❍	❍	❍	❍	❍	❍
Remaining Service Life	❍	❍	❍	❍	❍	❍
Asset Age	❍	❍	❍	❍	❍	❍
Level of Service	❍	❍	❍	❍	❍	❍
Deterioration Rate	❍	❍	❍	❍	❍	❍
Maintainability	❍	❍	❍	❍	❍	❍
Risk of Failure	❍	❍	❍	❍	❍	❍
Constructability	❍	❍	❍	❍	❍	❍

7) Please rate the following economic decision criteria in terms of their relative importance for selection of municipal infrastructure projects:

	Very low	Low	Medium	High	Very High
Project Cost	❍	❍	❍	❍	❍
Indirect Cost	❍	❍	❍	❍	❍
Agency Cost/ Benefit	❍	❍	❍	❍	❍
Social Cost/ Benefit	❍	❍	❍	❍	❍
User Cost/ Benefit	❍	❍	❍	❍	❍

8) Please rate the following financial decision criteria in terms of their relative importance for selection of municipal infrastructure projects:

	Very low	Low	Medium	High	Very High
Available budget	❍	❍	❍	❍	❍
Life Cycle Cost	❍	❍	❍	❍	❍
Financial Risk	❍	❍	❍	❍	❍
Asset Value	❍	❍	❍	❍	❍

9) Please rate the following environmental decision criteria in terms of their relative importance for selection of municipal infrastructure projects:

	Very low	Low	Medium	High	Very High
Effect during normal operation	❍	❍	❍	❍	❍
Effect due to failures	❍	❍	❍	❍	❍
Effect during construction	❍	❍	❍	❍	❍

10) Please rate the following social decision criteria in terms of their relative importance for selection of municipal infrastructure projects :

	Very Low	Low	Medium	High	Very High
User's Opinion/ Complaints/ feedback	❍	❍	❍	❍	❍
Public demands (usage)	❍	❍	❍	❍	❍
Proximity of project to major urban areas	❍	❍	❍	❍	❍
Geographical distribution of funds	❍	❍	❍	❍	❍
Safety	❍	❍	❍	❍	❍
Effect during operations	❍	❍	❍	❍	❍

11) Please rate the following category of decision criteria in terms of their relative importance in your municipality (if you are not currently with a municipality, please refer to your previous experience with a municipality or to your advice to municipalities as a consultant - this will apply to all questions):

	Very low	Low	Medium	High	Very High
Technical/ Engineering Parameters	❍	❍	❍	❍	❍
Economic Parameters	❍	❍	❍	❍	❍
Financial Parameters	❍	❍	❍	❍	❍
Environmental Parameters	❍	❍	❍	❍	❍
Social Parameters	❍	❍	❍	❍	❍

12) Please list any other category/set of decision criteria which might influence the selection of municipal infrastructure projects for your municipality and then please rate them as before:

1	________________________________
2	________________________________
3	________________________________

13) If you think there can be more decision criteria for each category, please list one decision criterion for each group which might be significant and important for selection of municipal infrastructure projects and then give a rating to them, as before:

1. For Technical/ Engineering Parameters:	________________________________
2. For Economical Parameters:	________________________________
3. For Financial Parameters :	________________________________
4. For Environmental Parameters :	________________________________
5. For Social Parameters :	________________________________

14) Does your city believe that decision criteria for selection of municipal infrastructure should be same for different types of infrastructure:

- ❍ Yes
- ❍ No
- ❍ No Answer

15) If you checked "No" or "No Answer" to previous question, please select one or more of the following options which are relatively closer to your municipality's opinion:

- ❑ Decision criteria should not be the same, but in practice it is not worth it to create or impose new type of complexity to the decision making process
- ❑ Although the decision criteria should not be same, but in reality they are not very similar
- ❑ Decision criteria should not be same, but due to lack of knowledge, information, they might be the same and apply for all type of municipal infrastructure
- ❑ Decision criteria for each type of infrastructure are very different and they must be clearly determined for each type
- ❑ None of above given options is close to my opinion (Please specify your idea briefly below)
- ❑ Other (please specify)

If you selected other, please specify

____

Additional comments

____

16) Please check THREE (3) most important reasons that increase the complexity of the decision making process for the selection of municipal infrastructure projects:

- ❑ Lack of accurate input data
- ❑ Lack of application of appropriate technology
- ❑ Lack of training program for personnel which are involved in decision making process
- ❑ Lack of appropriate cooperation among organizations and instituitions that they are part of municipal infrastructure asset management
- ❑ Dealing with multiple factors that may significantly affect the project
- ❑ Existence of multiple stakeholders
- ❑ Time Pressure
- ❑ Cost Pressure
- ❑ Variation in estimated cost and time of the project
- ❑ Other (Please specify them briefly below)
- ❑ Other (please specify)

If you selected other, please specify

____

Additional comments

____

17) Thanks for your participation. If you have any additional comment about this survey please specify below:

____

____

____

Table A.1 Summary of assigned scores by respondents to all the decision criteria and the group decision criteria

	Very Low	Low	Medium	High	Very High
Asset Condition	0	0	0	7	10
Remaining Service Life	1	0	7	7	2
Asset Age	3	5	6	3	0
Level of Service	2	2	5	5	3
Deterioration Rate	1	4	8	4	0
Maintainability	0	4	8	4	1
Risk of Failure	1	0	4	10	2
Constructability	1	2	7	7	0
Project Cost	0	0	4	10	3
Indirect Cost	1	5	9	2	0
Agency Cost/ Benefit	1	2	7	4	3
Social Cost/ Benefit	2	4	4	7	0
User Cost/ Benefit	1	4	2	10	0
Available budget	0	0	1	7	9
Life Cycle Cost	0	4	4	5	4
Financial Risk	0	4	4	9	0
Asset Value	4	4	5	4	0
Effect during normal operation	0	5	6	6	0
Effect due to failures	1	0	6	5	5
Effect during construction	1	3	7	6	0
User's Opinion/ Complaints/ Feedback	0	2	8	7	0
Public demands (usage)	0	0	9	7	1
Proximity of project to major urban areas	2	4	9	1	1
Geographical distribution of funds	4	8	5	0	0
Safety	0	0	4	6	7
Effect during operations	2	4	7	3	1
Categories of Decision Criteria					
Technical/ Engineering Parameters	0	0	4	9	4
Economic Parameters	0	1	4	10	2
Financial Parameters	0	0	4	11	2
Environmental Parameters	0	3	5	5	4
Social Parameters	0	5	5	5	2