UNIVERSIDADE FEDERAL DE PERNAMBUCO
CENTRO DE TECNOLOGIA E GEOCIÊNCIAS
DEPARTAMENTO DE ENGENHARIA DE PRODUÇÃO
PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA DE PRODUÇÃO

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DECISION-MAKING MODELS TO STRUCTURE AND SUPPORT URBAN WATER SUPPLY PROBLEMS

RECIFE
2018

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PhD thesis submitted to UFPE to obtain the degree of doctor as part of the requirements of the Programa de Pós-Graduação em Engenharia de Produção.

Research area: Operations Research.
Advisor: Prof.ª Danielle Costa Morais, Doutora.

RECIFE
2018

Catalogação na fonte
Bibliotecária Margareth Malta, CRB-4 / 1198

M772d Monte, Madson Bruno da Silva.

Decision-making models to structure and support urban water supply problems / Madson Bruno da Silva Monte. – 2018.
121 folhas, il., gráfs., tabs.

Orientadora: Profa. Dra. Danielle Costa Morais.
Tese (Doutorado) – Universidade Federal de Pernambuco. CTG. Programa de Pós-Graduação em Engenharia de Produção, 2018.

Inclui Referências.

Texto em Inglês.

1. Engenharia de Produção. 2. *Value-focused thinking*. 3. FITradeoff. 4. Gestão de recursos hídricos. 5. Decisão em grupo. 6. Teoria da escolha social. 7. Intensidade de preferência. I. Morais, Danielle Costa. (Orientadora). II. Título.

UNIVERSIDADE FEDERAL DE PERNAMBUCO
PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA DE PRODUÇÃO

PARECER DA COMISSÃO EXAMINADORA DE TESE DO DOUTORADO DE

MADSON BRUNO DA SILVA MONTE

"DECISION-MAKING MODELS TO STRUCTURE AND SUPPORT URBAN WATER SUPPLY PROBLEMS"

ÁREA DE CONCENTRAÇÃO: Pesquisa Operacional

A comissão examinadora composta pelas professoras abaixo, sob a presidência da primeira, considera o candidato MADSON BRUNO DA SILVA MONTE **APROVADO**.

Recife, 27 de Junho de 2018.

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ACKNOWLEDGMENTS

First, I would like to thank God, for the gift of life and the opportunities that have culminated in this moment.

I would like to express my sincere thanks to my advisor Prof.ª Danielle Morais for the shared knowledge, for the patience, availability and also for the criticism that make me evolve. I hope our partnership is perennial.

I am grateful to all professor of PPGEP, especially to my evaluation committee, Prof.ª Ana Paula Costa and Prof.ª Luciana Alencar, for the assistance and contributions to my work during doctorate. I also thank Prof. Adiel Filho for the academic and professional encouragement.

I thank all the collaborators of the Departamento de Engenharia de Produção, especially the PPGEP secretariat.

I am grateful to Compesa for collaborating with the development of this work, providing data and access to its managers. I also thank CAPES and CNPq for funding this research.

Thank you to my family for encouragement, warmth, love and understanding the distance from being dedicated to this work. An especial thank you to my parents, Mario and Ianê for being examples of love, unity and goodness and to Makson for the brotherhood. Thank you to my parents-in-law for the support and great spur. I deeply thank my sweetheart wife and my dear daughter Maria Isabel for the best for filling my days with the best feelings that a person can have.

Thank you to my friends with whom I shared good and bad moments in this journey, especially to Ciro and Jadielson, and to my DNW friends Annielli, Leão, Marcella e Susane. I also thank Lucimário and Naiara for the companionship.

“Making decisions and exercising volition are very fatiguing, especially if they have to be done hurriedly and without the help of the subconscious.”

Bertrand Russell (1930)
The Conquest of Happiness

ABSTRACT

Water supply systems in urban areas may become deficient due to increasing demand, which accompanies population growth but is further jeopardized by equipment aging and problems related to maintenance management as well as water rationing. Moreover, operating the system involves a huge number of issues which a decision-maker must address simultaneously. Therefore, the use of tools to aid the decision process is quite relevant in providing a better grasp of the problem and to generate a recommendation that better meets the wishes of decision-makers. This thesis demonstrates such situations in two cases, treating a water system management and a maintenance management of equipment for water distribution. The first case deals with individual decision-making and a model is developed based on Value-Focused Thinking for problem structuring phase, but requiring only partial information in the multi-attribute analysis by FITradeoff, entailing less effort to achieve the ideal alternative according the manager preferences. It yielded a deep analysis of his reasoning, which was transcribed through the objective's hierarchy, and reached a solution to the problems of the local water supply system. However, as water resource management problems involve more than one decision-maker, and in the second case this thesis deals with group decision making, particularly Social Choice Theory. In traditional voting procedures, individuals are required to inform their preferences into a single choice or a ranking of alternatives. In this respect, the second case analyze the management of preventive maintenance of water pumps, developing a voting model which individuals' preferences were described through reliability engineering models and aggregated through quartile-based voting, which had its properties demonstrated. Collected information from individuals may not be enough to represent their real individual wishes. Consequently, the result of the aggregation of preferences may be distorted, and not representative of group preferences. A social choice function considering the intensity of preference over the alternatives has been developed to meet this need. Therefore, this thesis also presents a new voting method in which individuals' preferences are elicited based on an adaptation of the Simos procedure aiming to evaluate the alternatives and generate scores that are additively aggregated. Simulation and sensitivity analysis are performed, proving easy and intuitive for application to any group decision environment. Moreover, the model is axiomatically characterized and has its limitations presented in terms of Arrovian social choice theory.

Keywords: Value-focused thinking. FITradeoff. Water resources management. Group decision-making. Social choice theory. Intensity of preference.

RESUMO

Em áreas urbanas, os sistemas de abastecimento de água podem se tornar deficientes no atendimento aos consumidores por diversas razões, dentre elas o aumento da demanda devido ao crescimento populacional dos grandes centros, bem como o envelhecimento dos equipamentos utilizados no sistema causado por uma gestão da manutenção inadequada. A operação desses sistemas envolve uma grande quantidade de assunto que o gestor deve avaliar concomitantemente. Portanto, o uso de ferramentas que apoiem o processo decisório nesses ambientes é importante, pois promovem uma melhor compreensão do problema e podem sugerir uma alternativa que melhor atenda às preferencias dos decisores. Esta tese demonstra essas situações em dois casos, lidando com a gestão de um sistema de abastecimento de água e com a gestão da manutenção de equipamentos para esta finalidade. O primeiro caso trata um ambiente para um decisor, para o qual é desenvolvido um modelo baseado no *Value-Focused Thinking* para a fase de estruturação do problema e na fase de avaliação multiatributo requer do decisor apenas informação parcial a partir do FITradeoff, fazendo com que menos esforço seja despendido para encontrar a melhor alternativa de acordo com suas preferências. É exibido para este caso todo o raciocínio do decisor, descrito em termos da hierarquia de objetivos, a partir da qual se cria alternativas para solucionar os problemas de abastecimento de água. No entanto, como problemas de gestão de recursos hídricos envolvem mais de um decisor, no segundo caso, esta tese lida com decisão em grupo, particularmente com a Teoria da Escolha Social. Em procedimentos de votação tradicionais, geralmente requerem-se dos indivíduos que informem suas preferências em termos de uma única escolha ou um ranking de alternativas. Dessa forma, o segundo caso analisa o planejamento das manutenções preventivas para bombas utilizadas na distribuição de água, desenvolvendo um modelo de votação onde as preferências dos indivíduos são descritas a partir de modelos de engenharia de confiabilidade e posteriormente agregadas pela votação baseada em quartis, o qual tem suas propriedades demonstradas. Percebe-se que a informação coletada dos decisores pode não ser suficiente para descrever as suas reais preferencias e consequentemente o resultado da agregação dessas preferencias pode ser destorcido, de forma que não representa de fato os anseios do grupo. Portanto, esta tese desenvolve um procedimento de votação que considera intensidade de preferencia entre as alternativas com um modelo baseado numa adaptação do procedimento de Simos para avaliação de alternativas, o qual gera as pontuações para as alternativas que são somadas para obtenção do desempenho global. São realizadas simulações e análise de sensibilidade, mostrando a facilidade de se aplicar esse modelo sendo possível para quaisquer situações de decisão em grupo. Além disso, o modelo é caracterizado axiomaticamente e tem suas limitações apresentadas em termos das condições de Arrow da Teoria da Escolha Social.

Palavras-chave: *Value-focused thinking*. FITradeoff. Gestão de recursos hídricos. Decisão em grupo. Teoria da escolha social. Intensidade de preferência.

INDEX OF FIGURES

INDEX OF TABLES

CONTENTS

1 INTRODUCTION

Water supply systems may face serious problems which prevent water services from being performed with acceptable quality. Such reasons generally include aging equipment, accompanied by inadequate maintenance management; old projects of water supply and distribution networks, which do not support the growth of the local population; and sometimes the unavailability of water in its sources, which requires water rationing. Such deficiencies are common in developing regions. These situations demand that the water supply company intervene so as to improve system performance.

Water losses are also of great relevance in this context. According to the Trata Brasil Institute, Brazil wastes 37% of produced water, accompanied by financial losses of approximately 8 billion Brazilian reals (TRATA BRASIL, 2017). The water loss index is even higher in the North and Northeast Regions of Brazil, as in Pernambuco, wherein this index is around 46%. Water losses are inevitable, but it is possible to control them, reducing to acceptable levels. Japan is the flagship country in this context, since it reaches only 3% of water losses (BBC, 2018). The importance of analyzing the water loss index derives from the main variables that compose this measurement: leakage in the water distribution network, measurement errors, waste of water, and water misappropriation (MCKENZIE; SEAGO, 2005). Therefore, this index carries information regarding some aspects which the managers of water systems must address: issues related to the operation of the water system and issues surrounding population education and the exercise of citizenship.

Various actors are involved in decisions on water distribution; each one plays a different role and suffers the consequences of actions differently: population, government, regulatory agencies, and water companies. They have different points of view and may consider different groups of criteria when analyzing the context, which consequently leads to conflicting opinions.

The department which manages water system operations has a strong connection with all of these spheres because it is responsible for executing actions, managing system performance and conducting maintenance and rehabilitation in the water system. Furthermore, it should address water company's strategic objectives in order to deal with the established budgetary constraints, to comply with regulations and to meet population demands. The decision problems studied in this thesis are inserted in these contexts.

A decision-making process is very labor-intensive, as can be seen from the high complexity of the management of urban water resources. When a problem is not yet structured, decision makers need tools to support them in making the right decision. Such support is necessary from the collection of information, the identification of alternatives and criteria, as well as the stage of evaluating alternatives. In an environment with several individuals, support can be necessary for more than one decision maker, who should also be concerned about making a decision that represents the group's will.

These aspects lead to the necessity of expanding the studies in decision making and the development of new models with which to support this task in the urban water resources environment, aiming to solve the problems of water systems while considering the objectives of the involved individuals and how the preferences of various decision makers can be aggregated.

1.1 Relevance of the study

High complexity is an inherent characteristic in the management of water resources, as the consequences have major relevance in the social, economic and environmental spheres. In addition, actions usually involve large financial volumes and the impacts are felt thereafter for a long period of time. They may have numerous criteria, and may involve several decision makers and stakeholders (URTIGA; MORAIS, 2015). The population is an important stakeholder, as water distribution is the provision of a public service. Thus, problem structuring and decision making in this type of environment are often exhaustive for decision makers while also considering the properties of decision-making models, which can often lead to non-assertive decisions or inconsistencies in their statements (WEBER; BOCHERDING, 1993).

Regarding the maintenance of water systems, different models can be proposed for evaluating their characteristics. Moreover, when properly applied, a model serves as a tool for choosing the maintenance policy to be adopted. However, the choice of criteria to be optimized depends on the decision maker and this choice can lead to a conflict, since the policy that optimizes one criterion does not necessarily optimize all others (DE ALMEIDA-FILHO et al. 2016). This same aspect occurs when considering the management of operations of water supply, especially when seeking actions with which to improve the quality of the water service.

Therefore, the use of problem structuring methods (PSM) and multi-criteria decision-making (MCDM) models plays an important role in solving these types of problems. Once the solution must reconcile the views of both managers and consumers, it is also important to apply a procedure that aggregates preferences. In such cases, in addition to conflicts between individual criteria, it is necessary to deal with conflicts between different opinions.

Regarding group decision making, traditional models generally rely on poor information on the preferences of individuals. In these situations, the results of aggregation may not represent the group's actual preferences (VARGAS, 2016). This is the main reason for considering preference intensity among the alternatives. However, the more information is required from individuals in a model, the less viable its application. Furthermore, choosing a model through which to aggregate the preferences of decision makers, one must consider the characteristics of the decision environment and the properties of the models (NURMI, 1983). Even though there is not a perfect method, this does not prevent finding a solution that represents the collective willingness.

Although the models developed in this thesis are discussed in the context of the management of urban water resources, the proposed models can be applied in other decision environments.

1.2 Objectives

1.2.1 Main objective

To develop decision support models for an individual and for groups of individuals in the context of water management, reducing the effort of the decision maker without compromising the quality of the recommendation.

1.2.2 Specific objectives

To achieve the main objective of this work, the following specific objectives are addressed in this thesis:

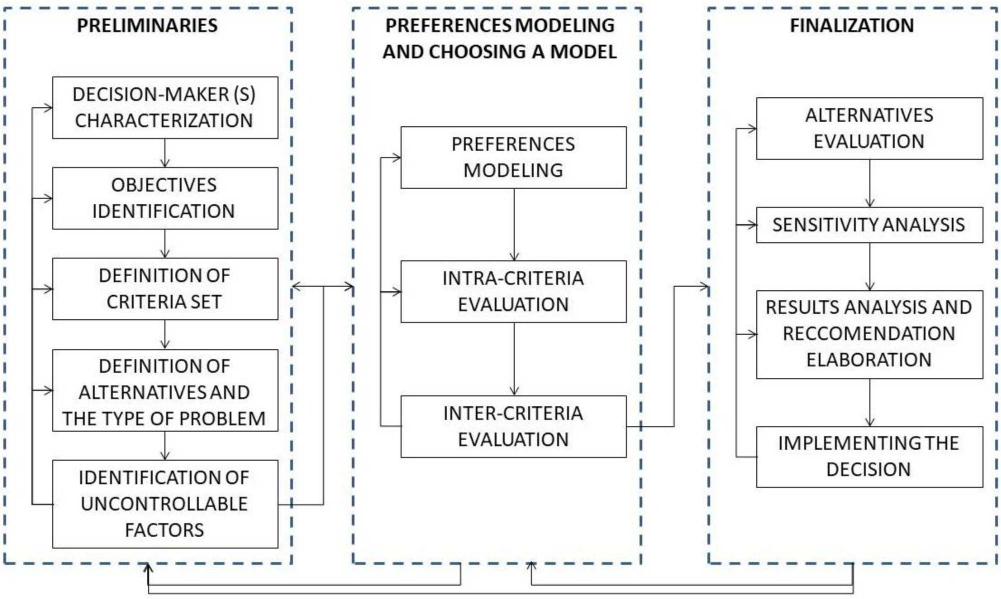
- To develop a decision model through which to support decision makers in problem structuring and the recommendation of an alternative.
- To develop a model for supporting group decision making, based on the theory of social choice.
- To illustrate the developed models in the context of urban water management.

- To enrich a voting procedure by considering the intensity of preferences in individual elicitation.
- To test the voting models through simulation and sensitivity analysis.
- To describe the properties of the models and their applicability.

1.3 Methodology

Studies conducted in this thesis involve the development of decision-making models, which are inserted in the operations research area. The research field is that of water resources management, specifically urban water management. The selected regions are located in Recife Metropolitan Area and were defined by the managers of water companies, who are also called decision makers. This thesis comprises three models for supporting decision making. In order to develop these models, it is applied the procedure for solving decision problems proposed by De Almeida (2013), as presented in the framework of Figure 1.

Figure 1 – Framework of a procedure for solving problems



Source: de Almeida (2013)

The first model is developed to solve choice problems, since an alternative to solving the problems of water supply was desired for a non-structured problem. The model is based on Value-Focused Thinking (VFT) (KEENEY, 1992) and FITradeoff (DE ALMEIDA et al., 2015) approaches, supporting the decision maker in the definition of the problem, preferences modeling and recommendation of an alternative. The alternative is selected based on decision-maker statements elicited in interviews. This model supports only one decision maker.

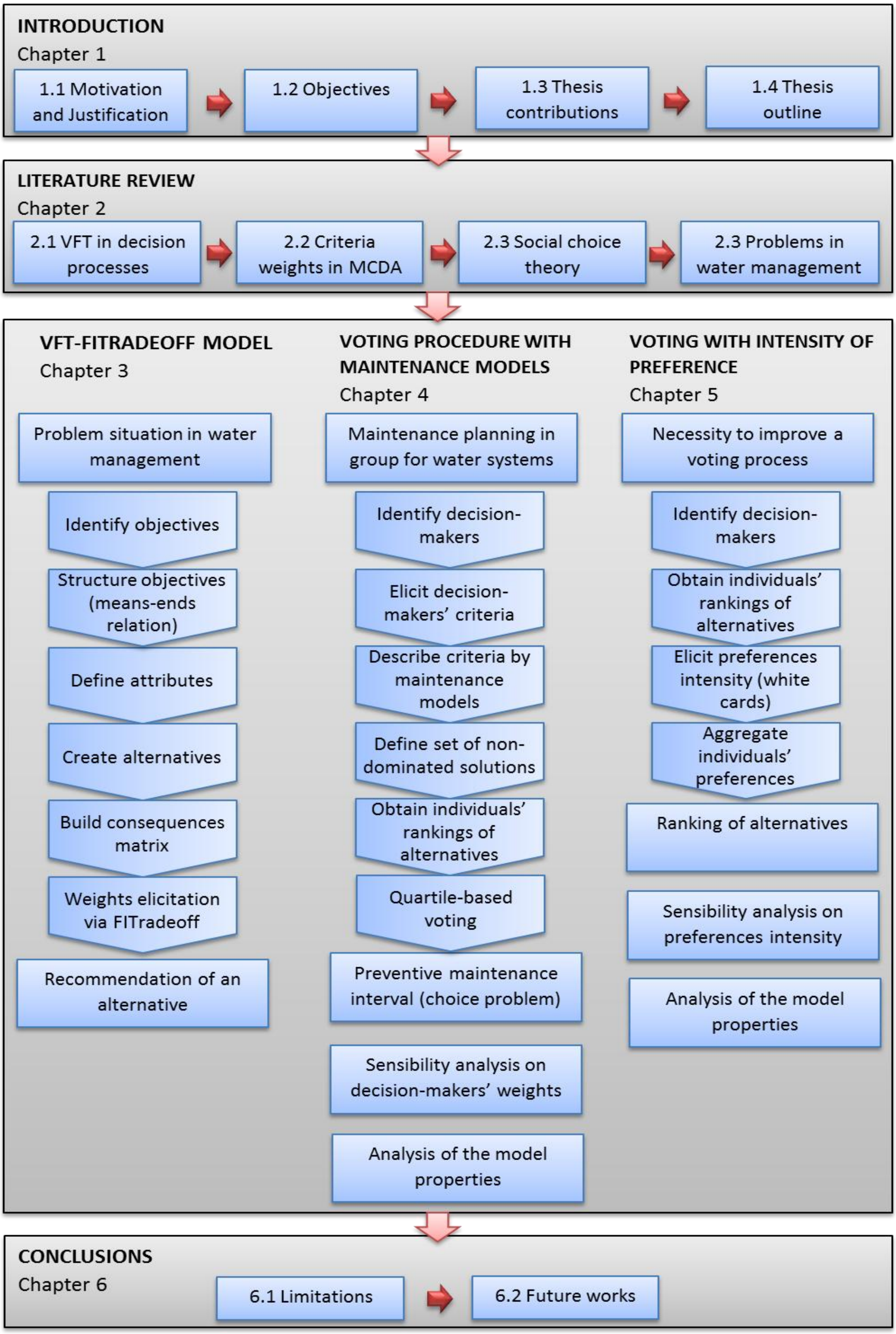
The second model is developed to solve choice problems for group decision making. The object of the study is the definition of a preventative maintenance interval for wells used for water distribution. Preference aggregation is based on social choice theory (MORAIS; DE ALMEIDA, 2012), with individuals' preferences described in terms of reliability and maintenance engineering models and evaluated by the multi-criteria decision-making model most suitable to each individual reasoning (DE ALMEIDA-FILHO et al., 2017).

The third model is developed to solve ranking problems for group decision making. Moreover, the model includes the intensity of preferences of individuals over alternatives before aggregation. This model is based on an adaptation of Simos' procedure (FIGUEIRA; ROY, 2002) for alternative evaluation. Simulations are performed with different sets of alternatives considering three and four individuals. The analysis of this model considers sensitivity analysis by varying the intensity of preferences, the removal of alternatives and comparison of the results with application of other procedures. Social choice theory also provides the means for describing the properties of the presented models for groups.

1.4 Thesis outline

Besides the introduction, this thesis presents five other chapters as in Figure 2. Chapter 2 presents a review of the literature. Chapter 3 describes the case study in the context of urban water supply and develops a decision model for this environment. Chapter 4 presents how to evaluate voting methods and performs the analysis of the quartile-based procedure with application in urban water management. Chapter 5 develops a voting model with preference intensity, presents simulations, sensitivity analysis, and the demonstrations of the properties of the proposed method. Final considerations and future work are presented in Chapter 6.

Figure 2 - Structure of the thesis



Source: This research (2018)

2 LITERATURE REVIEW

This chapter presents a review of the literature addressing the developments of methods and some applications which are relevant in the issues dealt in this thesis. Thus the following sections comprise problem structuring methods, focusing in Value-Focused Thinking and its applications; establishment of weights in multi-criteria decision aid models; social choice theory, presenting the mainly voting procedures and the most recent developments on this study field; and applications of decision models in the context of water resources management.

2.1 VFT in decision processes

A decision-making process demands hard work from decision-makers. The task is more laborious when the situation is not well structured in the DM’s mind. Such scenario highlights the usefulness of methods that provide support for extracting information, logically organizing them, identifying the decision-makers’ objectives and attributes as well as for performing alternatives evaluation. Problem structuring methods (PSM) help decision-makers to identify relevant variables for a problem.

PSMs can be categorized as soft operations research since they deal with the qualitative and subjective aspects of the decision-maker (DM) and of the decision environment (MINGERS; ROSENHEAD, 2004). Thus, PSMs can describe and structure the problem, suggesting a solution even for highly complex situations. There is a huge list of PSMs but the most common among them are Strategic Options Development and Analysis (SODA), Strategic Choice Approach (SCA), Soft Systems Methodology (SSM), and Value-Focused Thinking (VFT). These methods share the feature of using graphical tools to represent the environment or the DM's reasoning in order to support the decision process. These tools are cognitive maps in SODA, rich pictures in SSM and the objectives structure in VFT (EDEN; ACKERMAN, 2004; CUNHA et al., 2016).

According to Keeney (1992), PSMs can be divided into methods focused on alternatives (AFT) or methods focused on values (VFT). The main difference between them is the limitation of AFT methods when focusing the DM’s reasoning on the already available alternatives while VFT seeks for create alternatives in order to meet the DM’s objectives, therefore achieving a more satisfactory result. VFT methodology constitutes a philosophy for problem understanding and resolution in itself, while all the other current methods are classified as AFT. Léon (1999) compared AFT and VFT methods by investigating their abilities to generate objectives. He demonstrated that VFT is more comprehensive since it covers more aspects of the problem with better quality of objectives description. Similar results were obtained by Arvai et al. (2001) using a risk management approach. They evaluated groups with AFT and VFT prescriptive decision processes and stated that beyond comprehensiveness, the VFT participants felt more comfortable with the process and more accomplished with the selected alternative.

Given such advantages, many researches have preferred to use VFT for problem structuring in various contexts. McDaniels and Trousdale (1999) applied VFT to help government and stakeholders in tourism planning and management in a rural region of the Philippines. VFT allowed them to raise the marketing potential of the area and proposed a ranking of alternatives to best develop the region. Also, still on tourism management, Kajanus et al. (2004) identified the fundamental objectives for tourism development in a Finnish region. However, they created a hybrid method for the alternatives evaluation based on SWOT analysis and the Analytical Hierarchy Process (AHP).

Dynamic fields of study, such as the telecommunications, are also good candidates for VFT analysis. Yoo et al. (2001) performed a value structuring on the strategic management of radio in mobile communication. The alternatives analysis was based on the Multiattribute Utility Theory (MAUT) to show the value's tradeoffs for this case. The mobile network was also object of study by Sheng et al. (2005) inside a telecommunication company, which laid the basis for the enterprise strategy through an extensive network of objectives. Sheng et al. (2010) studied the impact of the mobile technology in education, trying to better understand the benefits and hazards for students, teachers and trainers. The values of electronics industry have also been studied to identify its success factors for both the standard desktop commerce (TORKZADEH; DHILLON, 2002) and for mobile transactions (SIAU et al., 2004). VFT can also be applied to support decisions in high risk contexts such as market survival and organizational management (MERRICK et al., 2005a; VAN DER LEI; LIGTVOET, 2015). Merrick and Grabowski (2014) applied VFT at an oil company in order to improve its safety indicators through the identification of critical issues needed for achieving a reduction in the number of accidents.

Environment protection is also a study subject both for its importance and for its complexity. Hassan (2004) discusses the selection of material to be used in the construction industry. He considers the environmental aspect of the chosen material and, after VFT and an evaluation through Multriattribute Value Functions (MAVT), he demonstrated that reforested wood is the most compatible with the local environment and construction supplies demands. Alencar et al. (2011) studied the impacts of plaster waste disposal, as garbage generated by the construction industry. They involved several stakeholders in order to enrich the decision process when eliciting the objectives, the restrictions and the consequences of the actions. In that case, VFT supported the creation of better alternatives for dealing with plaster waste. Several applications of VFT in Brazil can be found in Morais et al. (2013) such as water resources management, waste management, and strategic planning of information systems.

Problems related to planning and managing water resources have innumerous criteria which can be considered simultaneously and may require the involvement of several DMs (DE ALMEIDA-FILHO et al., 2017). Furthermore, the population is generally one of the main actors in this decision process when it comes to the provision of a public service. With regards to that, Urtiga and Morais (2015) applied VFT with several participants from the local community, industry and government. The case concerned the use of a watershed and the benefits of VFT were noticed during conflict resolution before the negotiation process. Bosch et al. (2012) showed that successful planning of water usage requires the involvement of all stakeholders in the decision process both for development and implementation phases, while reflecting the community objectives and resources limitations. In such study, alternatives generated through VFT were ranked applying an Analytical Hierarchical Process (AHP). In the case described by Merrick et al. (2005b), an urban river basin was studied with the aim of improving water quality by reducing pollution and it involved a large group of researchers, politicians, community members and decision analysts. The objectives were structured in a workshop in which a multi-attribute function was also created to evaluate the alternatives.

2.2 Weights is multi-criteria decision-making

After structuring the problem, it is necessary to devise ways to evaluate the alternatives which is done by using multi-criteria decision aid (MCDA) methods. The researches in previous section, for example, use MAUT, MAVT and AHP for that purpose. VFT’s author (KEENEY, 1992) recommends the use of MAUT or MAVT depending on whether or not the situation deals with uncertainty.

An additive model can be represented as a function $V(a) = \sum_{i=1}^{m} w_i v_i$ where, in the case of MAVT, *V(a)* is the overall value of alternative *a*, $v_i(a)$ is the value of the alternative under the criterion *i*, and w_i is the scale constant or weight of this criterion (KEENEY; RAIFFA, 1976). In some studies, it is important to differentiate the term weight from scale constant, since the former refers only to the degree of importance of this criterion and the latter involves this and other subjects such as how much one is willing to lose in a criterion in order to have a gain in another criterion, due to the compensability of the additive function (KEENEY; RAIFFA, 1976). However, this thesis will differentiate neither the use of these terms nor between criterion and attributes.

A relevant issue in the literature of decision-making aid is the difficulty to obtain such criteria weights, being a task that requires a lot of the decision maker and may be subject to inconsistencies (DE ALMEIDA et al. 2015). There are several methods to obtain the weights which can be determined directly by the decision maker, can be elicited or, when none of these options is available, the substitute weights may be applied. According Weber and Bocherding (1993), these methods can be classified as:

- Algebraic, if the procedure determines the weights from an equation system formulated from decision-maker's judgments, or statistic if the weights are determined from a redundant set of judgments and derived with some statistical procedure such as multiple regression analysis;
- Holistic, if the procedure requires decision-maker to evaluate alternatives (rating or ranking them), or decomposed if it look at one attribute or attribute pair at a time;
- Direct, if the procedure ask the decision-maker to compare ranges of two attributes in terms of ration judgments, or indirect if the procedure infer weights from preference judgments.

De Almeida et al. (2015) presents a framework showing the approaches for elicit weights through partial information procedures. Regarding the preference statements, the procedure can be structured or no structured, require the information all at once or interactively, and in a flexible way or based on a fixed process. The partial information can be in the form of rankings, bounds, holistic judgments or arbitrary linear inequalities. The synthesis step can be the surrogate weights, decision rules, based on linear programming models identifying potentially optimal alternatives or based in simulation and sensitivity analysis.

It can be mentioned the most common methods for weights elicitation: swing (EDWARDS; BARRON, 1994), which asks decision-maker for assessments based on hypothetical alternatives with the best and worst performances in each criterion aiming to order them and after that, assessments are required regarding the contribution of each criterion on the overall value, from where the weights are established. In tradeoff procedure (KEENEY AND RAIFFA, 1976) the decision-maker is required to compare alternatives under the consequence space of the problem, which is defined from intra-criteria analysis. When the decision-maker finds the indifference between pairs of consequences, it is possible to establish a relation between the scale constants, which are defined including the condition that their sum must be 1. Besides these, other multi-criteria decision aid methods have their own structure to obtain the weights such as Macbeth (Measuring Attractiveness by a Categorical Based Evaluation Technique) (BANA E COSTA et al., 2005), AHP (Analytical Hierarchy Process) (SAATY, 1980) and SMAA (Stochastic multiobjective acceptability analysis) (LAHDELMA et al., 1998).

A problem with the additive model and other models is that in real-life decision-making, numerically accurate information rarely exists, furthermore decision-makers may experience difficulties because most people do not have the required cognitive capacity and also suffer difficulties regarding to the specification of the decision problem. In addition, there are cases where they prefer not to expose this information for a variety of reasons, such as ethics or confidentiality (FRENCH, 1995; ZIMMERMAN, 2000). Some approaches in the literature use information of ordinary or imprecise importance to determine weights of criteria and sometimes values of alternatives (WEBER; BOCHERDING (1993); DANIELSON; EKENBERG, 2017).

Methods using surrogate weights have appeared to supply the decision analyst with the information of the weights, although they are not provided by the decision-maker. Traditional methods for obtaining surrogate weights are described in Table 1, in which w_i refers to weight of criterion i, placed in R_i^{th} position by decision-maker from a set of N criteria (BARRON, 1992).

In such cases the only information required form decision-makers is the criteria ranking. In this same family of methods, there is the Ranking Order Centroid (ROC) which has a stronger mathematical background: according to Edwards and Barron (1994) the criteria order defines the space of solutions whose centroid has coordinates such that they coincide with the expected value of the weights vector. It can be defined as a linear programming model with objective function $\sum_{i=1}^{N} w_i = 1$ and restrictions based on criteria ranking $w_1 \geq w_2 \geq \ldots \geq w_N$. The answer of this problem is the weights set, obtained from $w_i = \frac{1}{N}\sum_{j=i}^{N}\frac{1}{j}$.

Table 1 - Surrogate weights formulas

Equal weights	**Rank sum**	**Rank reciprocal**	**Rank exponent**
$w_i = \frac{1}{N}$	$w_i = \frac{N - R_i + 1}{\sum_{j=1}^{N}(N - R_j + 1)}$	$w_i = \frac{1/R_i}{\sum_{j=1}^{N}\left(1/R_j\right)}$	$w_i = \frac{(N - R_i + 1)^Z}{\sum_{j=1}^{N}(N - R_j + 1)^Z}$

Source: This research (2018).

There is no guarantee of how good or how "correct" the solution can be since the "real" weights are unknown or even inexistent (in some objective sense). The quality of the decision using these tools was addressed by Barron and Barret 1996 applying a process with systematic simulations, but their way of validating results is strongly dependent on the distribution used for generating the weight vectors (DANIELSON; EKENBERG, 2017).

Simos (SIMOS, 1990 apud FIGUEIRA; ROY, 2002) proposed a procedure that allows a decision-maker to express his/her wishes regarding the importance of criteria. The elicitation is easily performed through "playing cards", in which the decision-maker indicates the degree of importance of each criterion and after normalization the weights are calculated. Figueira and Roy (2002) proposed an addendum to this procedure eliciting the ratio of preference between the first and the last criterion. These procedures are the basis of the voting procedure developed in chapter 5.

The most recent methodology deals with partial information, called Flexible and Interactive Tradeoff – FITradeoff (DE ALMEIDA et al. 2015). The authors made the process to elicit the scale constants more flexible since FITradeoff does not require the decision-maker to express a relation of indifference between consequences, as in the traditional tradeoff procedure. The process is based in comparing consequences stating only strict preference, becoming easier to the decision-maker. Furthermore, the interactivity of the method reduces step by step the set of potentially optimal alternatives until there is only one alternative and this is the recommendation to the decision-maker which corresponds to the same one by applying the tradeoff procedure if the individual is consistent in his/her statements. De Almeida-Filho et al. (2017) showed that this procedure requires less effort from decision-maker through empirical experimentation. More details are given in chapter 3 since FITradeoff is integrated to VFT in order to deal the problem of study case.

2.3 Social choice theory

Arrow's Possibility Theorem consists of two axioms and five conditions (ARROW 1950). Axiom 1 holds that for all pair of alternatives A_x and A_y, either $A_x\mathrm{R}A_y$ or $A_y\mathrm{R}A_x$. Axiom 2 establishes that for all A_x, A_y, and A_z, $A_x\mathrm{R}A_y$ and $A_y\mathrm{R}A_z$ implies $A_x\mathrm{R}A_z$. These two axioms define a weak order of the alternatives since '*R*' means a preference relation of strict preference or indifference.

The Arrow's Conditions are: 1) *R* should be defined for all admissible pair of alternatives; 2) the positive association of social and individual values; 3) the independence of irrelevant alternatives; 4) the condition of citizens' sovereign; and 5) the condition of no dictatorship. Thus, in satisfying both axioms, every social ordering satisfying conditions 1 and 2 are either imposed (violating condition 4) or dictatorial (violating condition 5).

Although Arrow developed the axioms for social choice functions in the 1950s, voting methods date back much earlier. In the 1770s, Borda developed a method that punctuates the alternatives according to the position they are placed in the individuals' ranking. The alternatives ranking is obtained by summing the points that each alternative received and organizing them in descending order (YOUNG, 1974). Borda counting does not have independence of irrelevant alternatives and, moreover, is quite susceptible to manipulations (BLACK, 1987). The Condorcet method (CONDORCET, 1785) performs a pairwise comparison between the whole alternative set. An alternative wins a comparison when it is chosen by the majority of the group. The alternative that defeats all others is the Condorcet winner. However, Condorcet does not ensure transitivity in preference relations (NURMI, 1999). The Copeland method (RICHELSON, 1978) is also based in pairwise comparison. However, it generates a score based on the difference between the number of times that an alternative defeats the others and the number of times that it is defeated. This feature solves the Condorcet method's intransitivity problem, and the Copeland method chooses the Condorcet winner when it exists (RICHELSON, 1978). Ackerman et al. (2013) and Cullinan et al. (2014) present models to deal with partially ordered alternatives.

The list of voting procedures is extensive. Nurmi (1983) presents a summary of various methods and analyzes them according to sets of criteria or properties of voting systems, which are detailed in Section 2.3.1. The best performance was obtained by approval voting, whereas Hare's and Coomb's methods most violate the list's criteria. Obviously, none of them respects all criteria and the choice for a method depends on the importance that each criterion plays in the situation to be treated. In this sense, Palha et al. (2017) presented a framework to aid in the task of choose a voting procedure.

Baharad and Dazinger (2018) simulated a situation for hiring an employee. However, there is no certainty regarding the ability of candidates because the committee members received partial information about these characteristics. So, considering the use of various voting procedures, the authors deducted the probability of the committee to choose a candidate with high ability and the "almost" rules demonstrate superior performance. Authors called almost rules the application of a method with a simple modification in the punctuation received by the second-ranked candidate.

Leyva-López and Fernández-González (2003) departed from individual ranking and applied the ELECTRE methodology to construct the fuzzy binary relation to represent the social preference. Herrera et al. (1995) obtained the collective linguistic preference through fuzzy majority and developed dominance concepts for their case. Herrera et al. (2005) developed a model that combines different types of information (numerical, interval and linguistic) and based on 2-tuple fuzzy linguistic they perform the aggregation of these non-homogeneous information. Munda (2012) also considered a non-homogeneous context, but modeling preference intensity by indifference and preference thresholds, while applying fuzzy preference relations to aggregation.

García-Lapresta et al. (2009) described the Borda count in terms of linguistic decision-making and considered different sets of individuals according to their alternative favoring. García-Lapresta and Martínez-Panero (2009) created a linguistic-based system using centered ordered weighted averaging (OWA) operators and an adapted 2-tuple model. Many of these models are based in pairwise comparisons. In this sense, Vargas (2016) developed the eigenvector method of pairwise comparisons, affirming that it does not violate the democracy condition. In the eigenvector method, each element a_{ij} of the matrix represents the intensity of preference of alternative i over alternative j. The author algebraically aggregates the individual matrices and obtains the alternatives scores by matrix eigenvector.

Cavallo et al. (2018) deal with cardinal preferences expressed in terms of pairwise comparison matrices and they proposed two ways to aggregate individual preferences. The matrices were defined considering an Abelian linearly ordered (ALO) group and for each social choice function proposed, two reformulations of Arrow's conditions were described to their analyses. Although Arrow's conditions have been rewritten for this specific case, the Arrow's impossibility remains, as the first procedure violates the axiom of intransitivity and the second one is dependent of irrelevant alternatives.

Silva and Morais (2014) use linguistic scale assessments and bring in a differential of allowing abstention. The aggregation is performed with a Borda-based function with some adaptation to avoid the Borda susceptibility to manipulation. Linguistic scale is also applied in the methods of majority judgement and range voting; however, instead of the individuals indicating preferences by comparing alternatives, they should provide the alternatives evaluations in a common language (BALINSKI; LARAKI, 2014). Besides the wealth of information gained using linguistic scales, another advantage of Silva and Morais' (2014) work and majority judgment models is that they do not require a pairwise comparison of the alternatives, which is interesting when the number of alternatives is large.

The first step of majority judgement is to define the "language" from which the individuals represent their alternatives evaluation. Balinski and Laraki (2014) define it as a method of grading. The grades attributed to each alternative should be ordered, and the collective evaluation is equivalent to the median or middlemost value. The authors point out that the method is not susceptible to manipulations as the majority grade is not altered by attributing a too high or too low evaluation. As the odds of draw are high, Balinski and Laraki (2014) provide some tie-breaking rules. The basic difference between majority judgement and range voting is that range voting takes the average of the grades instead of the median.

The Borda Majority Count (ZAHID; SWART 2015) is another grading method. Natural numbers are attributed to each grade. So, the Borda Majority Count attributes the sum of the received grades to each alternative and ranks them according to this score. In the case of a tie, Zahid and Swart (2015) propose disregarding the lowest grade and the correspondents' votes from the scale and recounting the scores. Note that, even require another counting iteration, just one elicitation round is necessary.

Models of additive aggregation of individuals' preferences are methods that somehow perform the individual elicitation resulting in an individual score to each alternative in the alternative set, and the performances of the alternatives for the group are obtained by summing the individuals' scores. In such cases, the alternatives' ranking is given according to the descending order of the group performances or simply choosing the alternatives with the highest group score. From the methods already mentioned in this section, the Borda count (YOUNG, 1974) and Morais and de Almeida’s (2012) quartile-based voting are examples of this class of models. Moreover, the linguistic-based model of Silva and Morais (2014) and the Borda majority count (ZAHID; SWART, 2015) also perform additive aggregation of individual scores but with the characteristic of considering degrees of preferences to evaluate alternatives.

Morais and de Almeida’s (2012) method, despite having as an input the ranking of alternatives from decision makers, solves a choice problematic. Their idea is that individuals should focus on the most important alternatives: the most and the least desired. So, the procedure divides the rankings into quartiles, eliminating the alternatives of the central quartiles, scoring those from the first quartile and penalizing the least. In the studies on decision making, more precisely in the behavioral area, there are some texts that bring the reduction of the quantity of alternatives as a strategy for the individual decision making, which are showed below. These studies were carried out mostly in the 1970s and 1980s, trying to describe the decision-makers reasoning facing different levels of complexity, as well as seeking strategies for decision-making in complex environments.

Tversky (1972) presents a theory of choice called "elimination by aspects" (EBA). Each alternative is evaluated in terms of a set of aspects (constrained attributes), and at each stage of the process, one aspect is evaluated in order of importance and alternatives that do not satisfy the aspect are eliminated. This process is performed until there is only one remaining alternative, which is the choice of the decision maker. Note that there is some similarity with the lexicographic method (TVERSKY, 1972). Payne (1976) found that when the decision maker is dealing with two alternatives, a compensatory reasoning strategy is used and, as the number of alternatives increases, the decision maker seeks whenever possible to eliminate some alternatives to limit the amount of information to be processed, and then proceed with the additive evaluation. Similar result was found by Timmermans (1993), showing that there is a positive relation between the number of alternatives and the use of elimination strategies. Olshavsky (1979) provided several decision support techniques for individuals to choose which they would apply, and found that most preferred to conduct a first phase of elimination before some other model. In addition, Olshavsky (1979) shows that as the number of alternatives and attributes increases, a smaller percentage of the available information to carry out the assessment is used. Paquette and Kida (1988) studied four decision strategies, and found that strategies to reduce the amount of information processed lead to a reduction in decision time without significantly reducing the accuracy of choice. The EBA (TVERSKY, 1972) was the method which presented the best result.

Another aspect is that Balinski and Laraki (2010) advocate that point-summing methods, i.e., methods that aggregate the individual scores to generate a ranking of the alternatives, or calculate an average of the individual scores, overwhelmingly favor centrist candidates. According them, a good voting procedure should neither favor nor penalize centrist candidates. These results were obtained through simulations experiments.

Therefore, the strategy of Morais and de Almeida (2012) method of reduce the alternatives can benefit the group decision process, since studies on the elimination of alternatives in decision-making show that this can increase efficiency without significantly reducing assertiveness, and can reduce the effect demonstrated by Balinski and laraki (2010) since the centrist candidates are precisely those of the intermediate quartiles and considered less relevant by Morais and de Almeida (2012).

2.3.1 Properties of voting procedures

The properties described below are well established in the literature and most are closely related to the conditions and the Arrow's Impossibility Theorem (ARROW, 1950). These properties are divided into three classes (NURMI, 1983): 1) Condorcet properties (definitions 1 and 2), which are related to the choice of alternatives that defeat or are defeated by all the alternatives in the pairwise comparison; 2) Rationality properties (definitions 3 to 9), of which a large part comes from game theory and some of them were defined specifically to social choice theory, addressing on some behaviors expected from the voting systems in the face of changes in its input; and 3) Implementations properties (definitions 10 and 11), regarding its simplicity and easiness.

Definition 1: A method is called a Condorcet-winner if it always elects the alternative, which wins all alternatives in pairwise comparison, when this alternative exists (NURMI, 1983).

Definition 2: A method is called a Condorcet-loser if there is the possibility of choosing an alternative that is defeated by all others in the pairwise comparison (NURMI, 1983).

Definition 3: A procedure is monotonic if A_x is the winner by applying this procedure and after some individuals change their minds so that A_x is ranked higher than before, keeping the preferences over the remaining alternatives the same, A_x remains the winner (Nurmi 1983).

Definition 4: A procedure respects the Pareto-optimality condition if every individual in the group prefers A_x to A_y, and then A_y is not chosen (NURMI, 1983).

Definition 5: A procedure has the property of independence of irrelevant alternatives if for any pair of alternatives $\{A_x, A_y\}$, an individual preference over alternatives other than $\{A_x, A_y\}$ never exert any influence on the group ordering over $\{A_x, A_y\}$ (SUZUMURA, 2016).

Definition 6: Consider $C(A)$ as the social choice function over the set A. A' and A'' are nonempty subsets of A. A procedure has the path independence property if $C(A' \cup A'') = C(C(A') \cup C(A''))$ for *all* $A', A'' \in A$. In other words, the result of a procedure should be the same if applied over a set of alternatives and when applied separately over its subsets followed by the application on the winners of these subsets (SUZUMURA, 2016).

Definition 7: Consider $C(A)$ as the social choice function over the set A; A' and A'' are nonempty subsets of A. A procedure respects the Chernoff condition if $A' \subseteq A'' \rightarrow C(A'') \cap A' \subseteq C(A')$ for all $A', A'' \in A$. In other words, if an alternative A_x is chosen by a procedure over the set of alternatives A, A_x should also be chosen by applying the procedure over every subset of A containing the element A_x (SUZUMURA, 2016).

Definition 8: Consider two disjointed subgroups of voters G' and G''. A procedure is called consistent if by applying a certain voting procedure, the alternative A_x is chosen by both subgroups G' and G'', and by applying in the group $G = (G' \cup G'')$, A_x is also chosen. (YOUNG, 1974).

Definition 9: A procedure is called vulnerable to a no-show paradox if for a part of the individuals in the group it is better to opt by not voting than by voting according to their preferences (NURMI, 1999).

Definition 10: A procedure is simple if and only if one ballot is necessary to run the procedure.

Definition 11: A procedure is easy if and only if the procedure is implemented by applying just dichotomous inputs from individuals.

2.4 Structuring problems in water management

A review of problem structuring methodologies and multi-attribute analysis for the management of water resources in urban areas, revealed what aspects are generally considered as relevant in this type of decision environment. Studies on the management of urban water are scarce compared to ones on the management of hydrographic basins and their use in energy production or in irrigation (HAJKOWICZ; COLLINS, 2007; CHRISTOPHE; TINA, 2015). In general, when it comes to the urban environment, the structuring of the problem focus on understanding the current state of the water company and/or the system’s infrastructure to remove barriers in order to improve the service or to create strategies for a desirable future scenario for the water system.

Since these surveys are usually conducted with water systems managers, it is quite reasonable for cost to be the most common criteria, carrying a high importance level (HAJKOWICZ; COLLINS, 2007). How cost is considered depends on the necessities of the problem and how the decision-maker sees it within the system, incurring different forms for its discrimination but obviously always needing to be minimized. For instance, Scholten et al (2014) included all activities related to system maintenance in the low cost attribute, which they described in terms of annual % per capita. The maintenance of water supply equipment in a poor region was described by Monte e de Almeida-Filho (2016), where costs for performing maintenance activities and operating the system were grouped into a single criteria. Palme et al. (2005) analyzed technologies for wastewater treatment and included the investment and the operation costs in the economic analysis.

Cost takes a more complex form when the analysis has a higher strategic level, requiring an economic evaluation. In such cases, the growth of the company (KEENEY et al., 1996) along with its economic development, and that of the population and the local government (KEENEY; MCDANIELS, 1992) become relevant variables. However, the more general the analysis, the more difficult the measurability of these factors.

The public and government’s appreciation of the services and actions provided is essential. That gives leverage to the social and governmental interests and can be brought up by the supply companies and government representatives, as seen in Joubert et al. (2003) who considered public and political acceptance an evaluation criteria for alternatives aiming to solve the disparities between water supply and demand in Cape Town city. This theme is also discussed in Palme and Tillman (2008), who addressed the problem of how to discern which indicators to evaluate for sustainable development for Swedish water utilities in specific. The public's acceptance is also considered in Lienert et al (2015) when building water infrastructure plans in Switzerland. Therefore, it is possible to perceive concerns regarding equity and fairness in services provision (HAJKOWICZ; COLLINS, 2007).

Since water is a public good, it is necessary for its management to involve the government, water companies and the population. When public involvement is not possible, studies try to account for variables related to their preferences and quantifies them as consumer's opinions (DE ALMEIDA-FILHO et al. 2016b; SRINIVASSAN et al., 2010). A favoring evaluation of the company from the public is quite relevant as it reflects the work of the water company and helps to secure funding from both the government, and the private sector when possible. For those reasons, some studies performed a group analysis involving representatives of various groups in the society, sometimes called stakeholders (JOUBERT et al., 2003; URTIGA AND MORAIS, 2015; LIENERT et al., 2015).

Besides public opinion, it is identified the guarantee of the balance between capacity of the system and demand for water, for both short and long term, as fundamental to managers. Thus, the system needs to be flexible enough to adapt to future demands (LIENERT et al., 2015; KEENEY; MCDANIELS, 1992; SCHOLTEN et al., 2014). Such variable is strongly considered in Lundie et al. (2004) and is accompanied by a vision for sustainability by performing a life cycle analysis of alternatives for water supply in a case study of Sydney, Australia. There is also concern regarding the safety of sewage disposal which is driven by the desire to protect the environment while guaranteeing the quality of the water coming from both the dams and the subsoil (LUNDIE et al., 2004; EDER et al., 1997).

Regarding the variables for measuring the performance of the alternatives, when it comes to water quality, physical-chemical, biological or aesthetical parameters are applied and the results are compared to standards used to judge compliance with local regulations (WALKER et al., 2015; FLORES-ALSINA et al., 2008). In this respect, Simon et al. (2004) created scenarios for the Berlin-Potsdam case using chemical parameters, the total discharge of local rivers, and the pollution level of storm water to analyze strategies for waste water treatment plants. They applied the Hassan diagram technique with iterations to promote improvements in the strategies until finding the best solution. When the performance of the system is evaluated, there is a quite relevant set of variables to be considered beyond financial interest. Thus, engineering maintenance criteria are useful since the decision-maker (DM) can use it to monitor the system’s reliability, failure rate, equipment availability, etc. (HYDE et al., 2004; SCHOLTEN et al 2014). Furthermore, these variables can be described for the entire system or just for a particular region/sector that may also require methodologies which deal with uncertainties (LEE et al., 2000).

2.5 Chapter remarks

This chapter provided an overview of the concepts and relevant publications on subjects that will be addressed in the next chapters of this thesis.

In multi-criteria decision-making models, defining criteria weights play an important role since it can substantially change the result of the model application. At same time, literature reports difficulties in establish weights, mainly through tradeoff procedure, which can also present inconsistencies in decision-makers’ statements.

On social choice theory, voting models have been developed for quite some time and in the 1950s, analysis of these methods becomes more expressive with the organization and development of “natural conditions” that a voting procedure must attend. From which, several criteria were developed for evaluation of methods, as well as it also encouraged the development of new procedures. More recently, some methods have been developed aiming to improve the voting process by considering more information about individuals’ preferences, however the difficulty in applying such methods increases considerably since most of them require the creation of a common language for individuals express their preferences.

Management of water resources, both for supplying urban centers and for managing water basins, has consequences of great relevance in the social, economic and environmental spheres. In addition, the actions usually involve large scale finances and its consequences can be felt immediately and far into the future. Even though there are several texts in this context, some of them have characteristics in common and others do not. Each decision-maker considers different aspects and criteria, judging them differently. Moreover, alternatives which are the best solution for a case do not have the same performance in other situations. This leads us to conclude that the problems-structuring and decision-making must be solved from an appropriately developed model for the case, which result are valid just for this situation.

3 MODEL FOR INDIVIDUAL DECISION-MAKING BASED ON VFT AND FITRADEOFF

Common problems in urban water supply systems can be demonstrated by analyzing it from the perspective of the operations manager of the local Water Supply Company. In this context, characteristics of the decision environment are identified in order to provide a framework for the decision-maker which yields a better understanding of the problem as well as creates alternatives, quantifying these alternatives in terms of the decision-makers' preferences.

VFT is a quite comprehensive method to aid decision-making, but the high level of exhaustion for both the decision analyst and for the DM is a drawback for anyone who fully applies the decision support model. This is why the authors seek to facilitate the application of the VFT using a tool that allows a more flexible elicitation from DM when obtaining the scale constants for the criteria or attributes and consequently in the alternatives evaluation.

In additive models, the definition of scale constants is a hard step in the decision process, since there is an axiomatic structure that must be respected (KEENEY; RAIFFA, 1976). Some authors have attributed these difficulties to the DM's inconsistent reasoning, requiring some assumptions in order to validate the results (WEBER; BORCHERDING, 1993; BORCHERDING et al., 1991). For that subject, de Almeida et al. (2016) proposed a flexible and more interactive process to perform the tradeoff evaluation called FITradeoff. The FITradeoff methodology only requires strict preferences information, instead of indifference relations required by traditional tradeoff. Furthermore, it is not necessary to provide complete information and in each interaction, the DM can judge if the result is satisfactory and can then opt for stopping the process or provide more pieces of information about his/her preferences. So, this softening proposed by FITradeoff reduces the efforts of DMs in the decision process and facilitates the use of MCDA methods in real situations (DE ALMEIDA-FILHO et al., 2017a).

The proposed model allows exploration of the DM's objectives and their structuring according to the characteristics of the decision environment as perceived by the DM. It further creates alternatives that best fulfill his or her wishes. Subsequently, the ranges of weights for the objectives' attributes are obtained, allowing the evaluation of alternatives for improvement of the water system, and further presenting the best alternative for the case with little information required from the DM. The recommendation is beneficial for both the water supply company and the population.

3.1 Context of the problem: a urban water supply system

Olinda is a city located in northeastern Brazil, neighboring the state capital of Pernambuco. Olinda has a population of 390,000 inhabitants and is one of the densest cities in Brazil, with approximately 9,068 inhabitants/km². However, the study area does not encompass the whole city and only covers the central region and its surroundings, with an estimated population of 120,000 inhabitants (IBGE, 2010). Figure 3 is a map of the region with the limits of the studied region highlighted, which corresponds to the central region and all of the preservation area (surroundings).

Figure 3 - Map detailing the studied area (Google Earth ®)

. *Source: The preservation area was defined by Olinda's Government (2017)*

The area under study is registered as a Brazilian national historical patrimony. Therefore, several restrictions are imposed to residents and service providers in order to preserve the some historical elements such as houses and monuments. Olinda's rich historical background makes it a popular touristic destination which receives tens of thousands of tourists every year, especially during Carnival season. A peculiarity of water services is that any activity related to pipeline maintenance and replacement, either for water or sewage, can affect historical patrimonies because it requires digging streets and sidewalks and, therefore, cause visual pollution besides interrupting supply to hotels, restaurants, commercial centers, and residents. The neighborhoods that surround the historical patrimony site are mainly residential and have a high population density comprised of low income families.

Water rationing is another characteristic of the local water supply system and is caused by the inability of the system to simultaneously provide water for the whole community and is further exacerbated by drought periods which force the government to control water consumption. Thus, Water Company divided the region into thirteen sectors as in Figure 4, which are supplied according to a schedule. These sectors were created based on current network connections, the presence of wells, the quantity of consumers in each area, and their type of tariff. The schedule is unbalanced in such way that there are discrepancies in service provision with some sectors receiving up to 50% (12 h/day) of the supply while others sectors receive only 15% of supply (~12h/week). It is worth nothing that the schedule is only for planned shutdowns periods but all regions are subject to unscheduled shortages due to system failure from power outages or equipment breakdown, which require corrective maintenance.

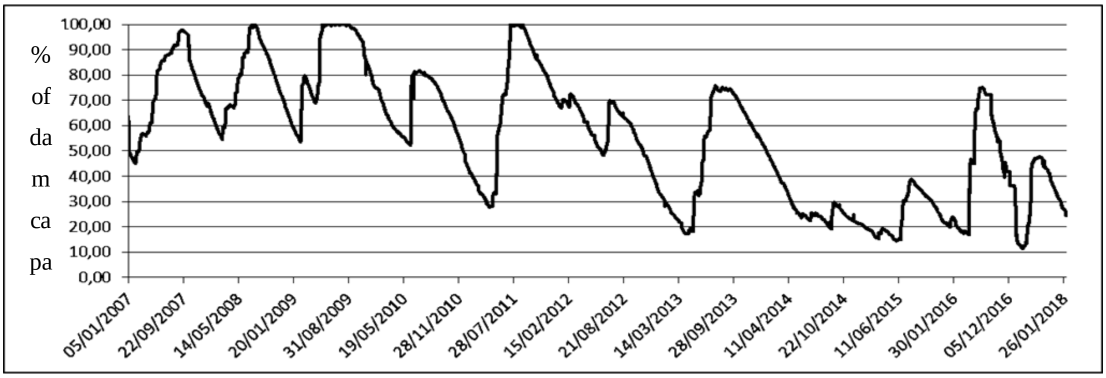
Figure 4 - Sectors of study area (Google Earth ®)

.Source: Sectors are defined by Water Company.

Water volume from raining seasons has been insufficient to replenish the Botafogo dam which supplies Olinda and three more municipalities. In the end of the first trimester of 2017, the dam's water capacity level was only 11%, the lowest ever recorded in the last ten years, as seen in the Figure 5.

Note that the graph presents a "saw tooth pattern," in which peaks illustrate the rainy periods which were very low for the years 2014 and 2015. The graph also reveals a reduction in the annual volume average with capacity reaching levels closer to its minimum during drought periods. In order to supplement the water supply for the region, wells were drilled to capture groundwater, feeding it directly into water networks or city reservoirs.

Figure 5 - Monitoring of the water level in the Botafogo dam



Source: APAC, 2018

However, the difference between the quantity of water produced and the system's demand could be reduced if the current large amount of water loss was cut down. This is a serious problem common to all regions in Brazil, but worse in the poorest ones. In Olinda, the estimated water loss makes up 55% of all produced water. Therefore, water loss is a serious concern for this region. Water loss is the difference between water produced, from the dam and the wells, and the sum of the consumption from all residences and commercial establishments according to individual water meter readings. According to the water company, major losses are the result of measurement errors; leaks in pipelines, valves, and other equipment; and water misappropriation.

Concerning payment for the service, the least privileged areas are charged based on a social tariff policy applied to low income families. The tariffs and some operations conditions are defined by Pernambuco Regulatory Agency (ARPE). This policy guarantees water access for all population and, as is well known, there is a correlation between water consumption level and the occurrence of diseases and public health problems (UN, 2017). The negative aspect of this pricing approach is the effect it has on supply management since revenue is not enough to keep the system at a satisfactory performance level, leading to poor service quality, lack of maintenance, which further aggregates the water loss problem requiring even more strict water rationing. Furthermore, the residents are not encouraged to save water, since the water bill does not increase to reflect water consumption. Regarding water misappropriation and saving water, there are citizenship issues involved in this study.

All services regarding sewer collection and treatment were outsourced. The contract signed through a partnership between government, the Water Company and outsourcing company is long term, valid for 30 years. The water company is only responsible for contract management and for receiving requests and complaints from the population, as well as for acting as an oversight agent. Consequently, the sewage services are beyond the scope of this research.

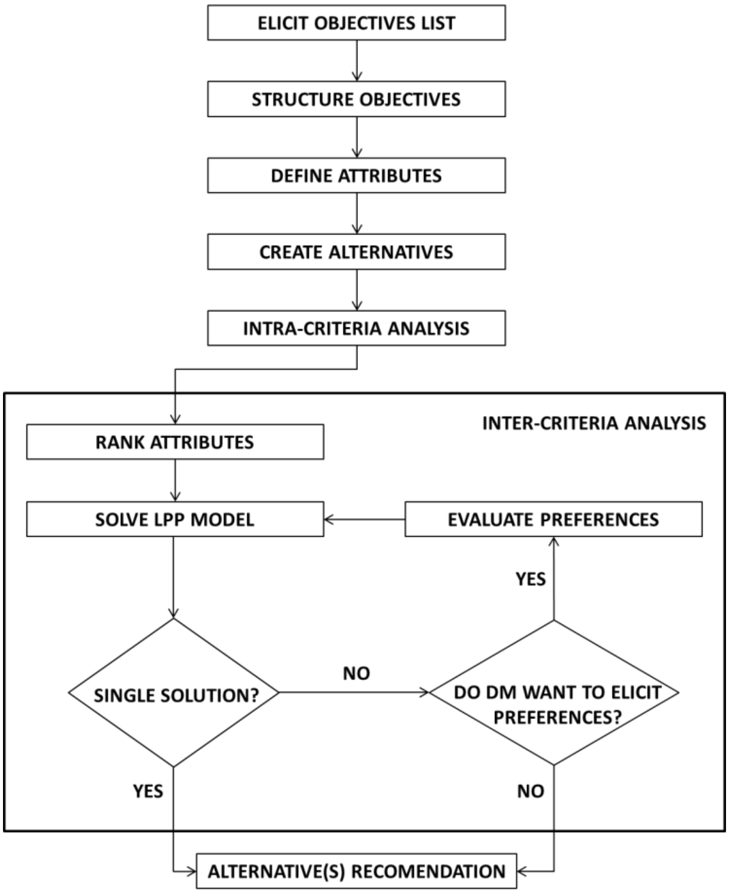
Overall, this Section briefly described the situation of the study site, highlighting some characteristics relevant to the problem's structuring conducted with decision-makers. This description also provided insight into the problem's complexity, which encompasses management operations, contracts, customer service, and financing. Based on the above, the goal of applying the proposed model is the improvement of water supply services in Olinda's historical center and its surroundings from the perspective of the Water Supply Company as described by the local operations manager.

3.2 Description of the model

The model is divided into four steps: in the first one, the principles of VFT should be applied in order to obtain the objectives and organize them into a network or hierarchy. The second phase is the creation of an alternatives set. The third one is the intra-criteria evaluation, where the decision analyst should define the attribute's scale and elicit their value functions. Finally, the fourth phase of the model encompasses the inter-criteria evaluation based on FITradeoff, where attributes' weights are defined according to FITradeoff heuristics, later performing the evaluation of the alternatives.

Figure 6 presents a schematic of the model proposed in this section with a simplification of the FITradeoff. The process can be worked within the FITradeoff software environment starting from the 'build the consequence matrix' box.

Figure 6 - Decision support model flowchart



Source: This research (2018)

3.2.1 Eliciting and structuring objectives

The first step of the VFT is objectives identification. It is a phase that demands hard work from the decision-maker. It is necessary to ask what the decision-maker (DM) wants to achieve in the referred situation. The decision analyst should encourage the decision-maker to obtain a detailed set of objectives. The techniques required to perform this step are well addressed in Keeney (1992; 1996), which uses questions about the wishes of DM, the consequences, generic objectives, goals and limitations, their strategy, and etc. All that data can be converted into objectives. Table 2 provides some examples of questions which can be used to elicit the DM’s objectives.

The output of this process is a list of objectives that will be structured next. It is important that these objectives be presented in a clear manner, in such a way that allows for defining related attributes, avoiding confusion from repeating the same objective with different wording, correlating a specific objective to others in order to create the objectives network, and consequently determining its impacts within the decision environment.

Table 2 - Sample questions for objectives elicitation

Approach	**Examples of questions**
Wish list	What do you want in this case? What is important to you?
Alternatives and consequences	What would be a perfect alternative? What is the worst scenario? What are the best/worst consequences for this situation? What are the consequences that concern you the most?
Problems	What is wrong? What should be fixed?
Restrictions	What prevents you from achieving your objectives?
Different perspectives	What would you do if you had another position in the company? How do you see the client's situation?

Source: Keeney, 1992; 1996

Within a specific context, the objectives can be classified as strategic, fundamental or means. When the scope of the DM's reasoning is expanded beyond the actual situation, the general objectives which guide the DM can be considered strategic. Strategic objectives are those on which the decision-making policy is based. Despite the great importance of strategic objectives in the decision-making processes, they are generally difficult to measure and control. Means objectives on the other hand, are easily handled but have a low level of representativeness. That is, a mean objective alone cannot be considered essential to the problem. However, fundamental objectives are those which present the desirable characteristics of relevance and yield a good level of measurement and control in order to reach the strategic objectives of the DM. Means objectives are those which contribute to the achievement of other objectives, and are used by the DM for this specific purpose. The links between these objectives are called means-ends relations.

The second phase then deals with value elicitation and consists of linking the objectives in order to understand how they behave together on the top of identify which are fundamental and which are at the base of the hierarchy. The objectives list is an input for this step, where the decision analyst asks the reason for the consideration of each of the objectives and consequently creates the means-ends relations. The answers to questions such as "*why is it important?*" can lead to other objectives and in that fashion, the objectives' structure is created step by step. When the DM experiences difficulties in expressing the reason for having listed a certain objective or he/she states that it is essential to the case study, it may be that the DM has found a fundamental objective. The result of this hard work produces the DM's values represented by a network of objectives which serve as the basis for identifying alternatives as well as establishing the attributes in order to measure their performances.

DM needs to define how to measure the performance of each objective. The variables that play this role are the attributes. Not all objectives are necessarily described through a single attribute, since an attribute may be related to more than one objective and an objective may be described by more than one attribute conversely. These attributes are defined in a way that describes the fundamental objectives with completeness, considering all the aspects involved for its attainment, should not be redundant. These attributes may be natural, when they are a direct measure of an objective; constructed, when no natural scale exists to measure an objective so it is constructed for a direct measure; or proxy, when it is difficult to select a natural scale in order to measure an objective directly. A natural attribute is preferable, but when there is no natural scale, constructed attributes can be used and, as a third option, it is necessary to identify possible proxy attributes (KEENEY; GREGORY, 2005).

3.2.2 Alternatives creation

In this phase, the decision analyst should explore the objectives generated and organized in the previous step in order to find (or create) the alternatives that best satisfy them. It is quite possible for lower level objectives to be potential alternatives for solving the problem. These objectives are so peculiar that they may characterize themselves as an alternative (ALENCAR et al., 2011). However, Keeney (1992) points out that it is necessary to look closely at the objectives' structure and apply it as a motive force for creating alternatives that would not naturally arise. Thus, it is necessary to scan all objectives, one at a time, and have the DM indicate alternatives that present the best performances for each one. After that, two objectives should be considered at a time and the DM indicates which alternatives best meet both objectives simultaneously. Next, three goals are considered together and so on.

At this stage, the differences between AFT and VFT become even more apparent, since VFT has a procedure that encourages the development of new alternatives (KEENEY, 1992; LEÓN, 1999). Therefore, this process provides a list of j alternatives which will later be analyzed through the methodology described in Section 3.2. It is necessary to describe the performance of the alternatives in each attribute and that data set is given the name of consequence matrix.

3.2.3 Intra-criteria analysis

When VFT is applied to general contexts, the attributes can be elicited in terms of utility functions or value functions. Generally, utility functions are applied when the consequences of the alternatives involve risk evaluation, while value functions are suited only for deterministic consequences evaluation (KEENEY; RAIFFA, 1976), although utility functions can also be used in cases that do not involve risk (HANEMANN, 1984). The present model is supported by an assumption of certainty in relation to the consequences of the alternatives. This is due to FITradeoff foundations, which only allows for the use of value functions.

Since the objectives' attributes are detailed, the next phase entails the construction of the functions which describe it. Each attribute i must have its value function v_i defined by using a 0 to 1 scale as a spectrum to represent consequences from worst to best. In the FITradeoff software, the local scale is automatically defined based on the consequences of the alternatives. The shape of the value functions should also be defined and in this study, linear value functions are applied according to Eq. 3.1, where $y_i(a)$ is the performance of alternative a in attribute i and, $y_{i\ min}$ and $y_{i\ max}$ correspond to the worst and the best performances within the alternatives set for attribute i.

$$v_i(a) = \frac{y_i(a) - y_{i\ min}}{y_{i\ max} - y_{i\ min}} \quad (3.1)$$

3.2.4 Inter-criteria analysis and recommendation

Assumes that the multi-attribute value function can be described as in Eq. 3.2. It is an additive model which aggregates the value functions v_i regarding the consequences x_i, for the entire attribute set $i = 1, 2, \ldots, n$ and the weights k_i normalized to sums up to 1 ($\sum k_i = 1$).

$$v(x) = \sum_{i=1}^{n} k_i v_i(x_i) \quad (3.2)$$

The FITradeoff procedure supports decision-makers and analysts when establishing the criteria's weights and indicates a solution in such way that there is no need to perform a complete tradeoff procedure. This is therefore a method which requires only partial information from decision-makers (DE ALMEIDA et al, 2016). The procedure is an interactive process and the decision-maker may include more information about his/her preferences at each iteration, thus enriching the model and further restricting the pool of viable solutions.

In its methodology, FITradeoff solves a linear program problem, for each criterion *i* and alternative *j*. (DE ALMEIDA et al, 2016; DE ALMEIDA-FILHO et al., 2017). The objective function of this system is the multi-attribute value function itself (Equation 2), which must have its performance maximized with information on the decision-maker's preference and the created alternatives. The authors of the FITradeoff methodology developed software to aid in this process. This decision support system (DSS) solves the problem using the information provided by the DM, which results in the respective attributes' weights in addition to calculating the alternatives' global performances.

The linear model is only restricted by the preference information provided in each iteration. In the first round, the only criteria information required is their ranking. If there are subsequent iterations, the DM is asked to compare consequences regarding attributes which automatically reduce weight space. FITradeoff's advantage lies in the fact that the comparisons may apply the strict preference relation, instead of just the indifference relation as requested in the traditional tradeoff procedure. The DSS indicates if the DM presents inconsistency in his/her assessments and the software is endowed with heuristics which seek to reduce the number of questions for the DM (DE ALMEIDA-FILHO et al., 2017).

After iteration, the model solves the problem by obtaining a range of weights for each attribute and identifies the potentially optimal alternatives. If a unique solution is found, the process is concluded with a recommendation. Otherwise, the DM is redirected to feed the model with more information regarding attribute comparisons. This process is repeated until a single solution is reached, but the DM may decide to end the process even with partial results. It is also possible for the process to result in more than one solution, depending on DM's preferences.

3.3 Application of the model

This section details the application of the model in the case study previously described. Three meeting were held: in the first was presented the methodology and the objective were elicited and structures, the second meeting comprised the establishment of attributes, alternatives creation and construction of consequences matrix and, in the third meeting, intra-criteria and inter-criteria analysis were performed supported by FITradeoff software, resulting in the choice of an alternative. In the last meeting, the decision-maker validated the process, reviewing his statements and agreeing with the obtained result.

3.3.1 Objectives elicitation and structuring

Following the VFT guidelines with the Olinda's operations manager, as presented in the Section 3.2, several characteristics of the system, which have been compiled into a list of 22 objectives, were presented as listed in the Table 3.

When asked about the best consequence for water distribution in Olinda, the manager replied that "*it would be a system operating without the need for rationing, with the minimum of supply interruptions and the same level of service for all sectors. In addition, operating with a low loss rate because this is waste of water and incurs high costs for water company"*. Thus, he said that it is crucial that the Water Company seeks to provide the best service to the population, with the highest possible level of quality, while at the same time being mindful of the company's financial health, guaranteeing its survival and generating profit.

When asked about the worst consequences, he answered that "*the worst situation is a collapsed system, in which there are uncontrollable water losses, wells deactivated due to contamination (as occurred with 2 wells), and the water company unable to act because of lack of personnel and money*".

When asked about problems that have been perceived, restriction and positive/negative actions, several subjects were listed:

"*The number of employees to perform network maintenance activities is small, which led the water company to outsource two companies; however some bureaucracies and contractual problems prevent their performance form being effective, causing delays to carry out maintenance activities*".

"*Water losses index is a serious problem and most occur in the capillary areas of network. However, there is a considerable portion of water losses that occurs before the water enters the managed area, since the dam is located very far form Olinda, almost 45 km. Regarding losses occurring in this course, there is nothing I can do now*".

"*Much of the unbalanced distribution in water supply calendar is due to problems in network, because of areas where maintenance is more deficient and there are more points of water losses. So, if more water is destined for these areas, the losses are even greater*".

"*I need to worry about the company's income and there are differences in water tariffs for the sectors. Thus, if consumers with higher tariffs have a greater availability of water, revenues will be higher. The same is valid for maintenance activities, which are more effective in these areas and the complaints of these consumers are prioritized. The worst in this policy is that areas which have a poor water supply do not have prospect of improvement.*

For this reason it is so important to attract investments to the water company, making it possible to invest in the entire system."

High water loss volume was a much-mentioned subject (N° 8), proving to be one of the manager's main concerns. It is further related to two strategic objectives, as can be seen later in the objective structure namely, to maximize the company's profit (N° 1) and to maximize service quality (N° 2) (Table 3).

Going forward with the questions, the manager also identified that the water company should reduce grievances to the population (N°4) caused by low water pressure in the network, poor water quality (N° 12) or by the lack of water, that can not only be caused by rationing, but also by interruptions from corrective and preventive maintenance activities. As far as water quality is concerned, the DM considered the replacement of old pipelines to be an objective (N° 18) along with the possibility of creating a plan to redesign the water supply system (N° 20). These objectives are also related to the reduction of the water loss volume, which possibly accounts for almost half of all wasted water.

In order to eliminate water shortage (N°13), the manager suggests that the company needs to find ways to increase water availability through such measures as drilling more wells in the region (N° 22) or, if possible, connecting the Botafogo dam to another water source (N° 21) such as the Capibaribe basin, which is the nearest and it is pouring untapped water. This last objective would also minimize supply problems in other municipalities. Reducing water shortage and losses, is progress towards reducing the difference between water demand and production (N° 9) which potentially eliminates water rationing and scheduled supply interruptions (N° 3), thus leading to better service provision.

The objectives structure is linked to another important objective of this study, the increase of the company's profit by minimizing operation costs (N° 6) while maximizing the provision of the company's financial resources simultaneously (N° 5). Attracting investors is directly dependent on the Water Company's reputation (N° 7) as perceived not only by the government and investors, but also by the population. To achieve better financial health, the manager needs to update existing clients' registrations (N° 14) to reflect new tariff adjustments along with registering those who divert water. Addressing the problem of water being diverted from the distribution network is also related to the water loss reduction objective. Moreover, in order to make better use of resources (N° 10), improving the company's image is of great importance, which can be done by raising awareness about water usage (N° 15) and by increasing the number of specialized staff (N° 16) – hiring new workers and conducting training with current ones – and by solving problems with other outsource companies that provide services such as equipment rental and civil construction to the water company (N° 17).

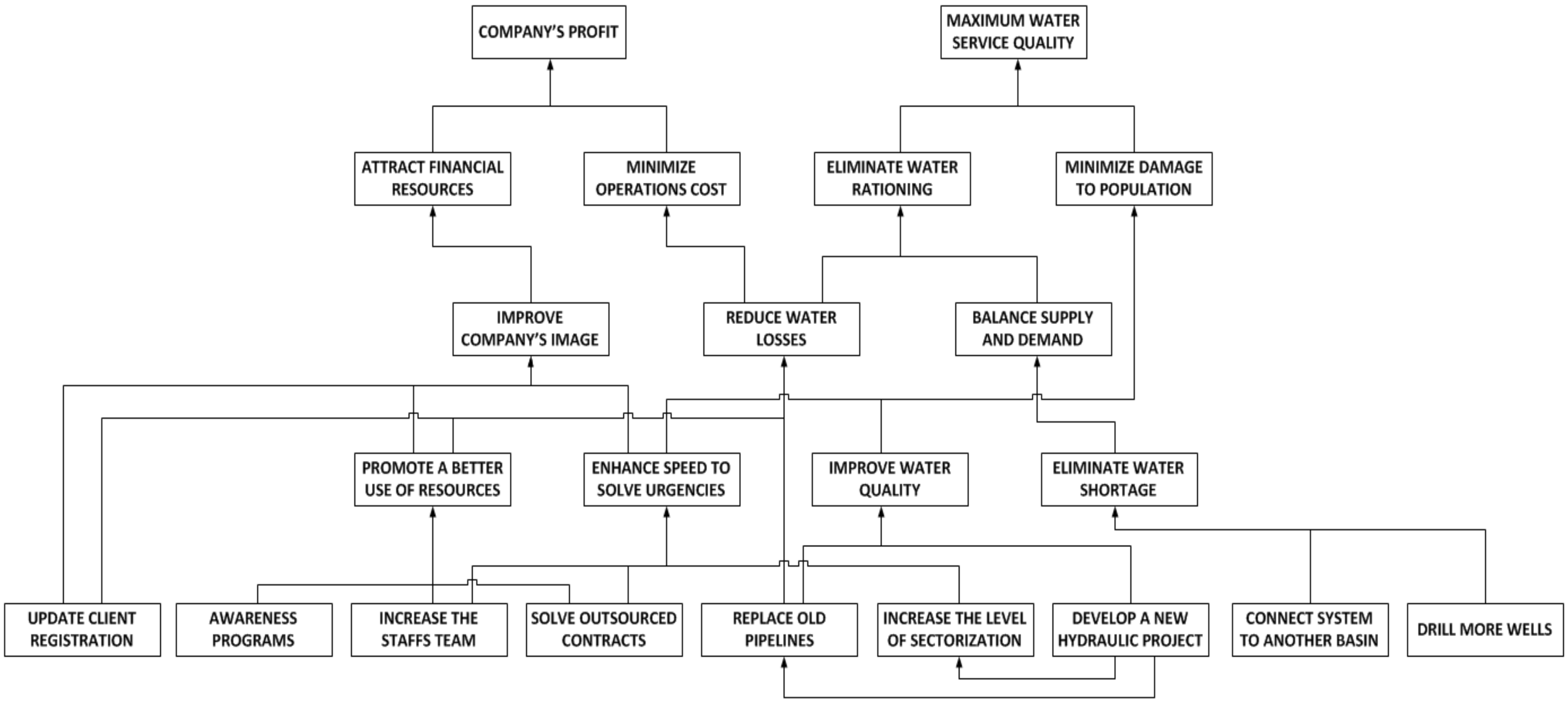
Table 3 - Objectives list

N°	**Objectives. To…**
1	Maximize the Water Company's profit
2	Maximize the quality of the water service
3	Eliminate water rationing and supply calendar
4	Minimize the damage to population
5	Attract financial resources
6	Minimize the cost to operate the water system
7	Improve the image of the Water Company to population and government
8	Minimize the water losses
9	Balance water production with the needs of the local population
10	Promote a better use of resources
11	Maximize speed when meeting consumers' requests, especially urgencies
12	Improve water quality
13	Eliminate water shortage
14	Regularize the clients and non-client's problems
15	Educate the population about wasting water
16	Increase the number of specialized technicians
17	Solve contract problems with outsourced service providers
18	Replace old water pipelines
19	Improve network maneuvers through wider sectorization
20	Develop and execute a new hydraulic project for the city of Olinda
21	Connect the Botafogo dam to another river basin
22	Drill more wells in the region

Source: This research (2018)

Finally, regarding to reduction of operational costs, the key is to reduce water loss volume. As previously seen, various objectives can be related to water loss volume. Furthermore, there are objectives related to the company's competency to perform its duties, especially the ones of an urgent nature (N° 11) such as broken pipes. The company's service improvement should include the creation of a maintenance plan, which can be carried out more efficiently by employing specialized staff (N° 16) and solving outsource problems (N° 17), in addition to performing maintenance tasks that improve the distribution system. The manager suggested increasing the number of distribution sectors (Nº 19), which are currently 13 for the studied region. The more sectors available, the smaller the areas affected by a breakdown, consequently simplifying maintenance and yielding less wasting of water and reducing the number of consumers affected by those occasions. DM pointed out that the best way to accomplish that is to develop a new hydraulic project for Olinda (N° 20) that would include all services necessary for the modernization of the water distribution system. Figure 7 illustrates the means-ends relations between the objectives described in this section while highlights their type and classifying them into means, fundamentals or strategic objectives.

Figure 7 - Objectives hierarchy



Source: This research (2018)

3.3.2 Attributes

The attributes describe the fundamental objectives in such a way that the performance of the alternatives in the study case can be quantified. There are four fundamental objectives and 16 means objectives, but not all of them have their own attribute and an attribute can be related to more than one objective. After discussion with the operations manager as described above, six attributes were defined and their description is shown below in Table 4.

The cost of implementing a given alternative (COST) is an indispensable attribute and includes the investment needed to execute the necessary actions as well as the cost to operate it moving forward. Therefore, the limits are related to the approximate cost of the alternatives presented in the next section and the lower the cost (measured in millions of Brazilian Real), the better the alternative for the water company.

The increase of water volume feeding the system (WFLO) is a variable that measures the degree of reduction in water shortage, fundamental objective for which maximization is desirable. Note that it is also related to the objective of balancing water supply and demand. In addition, in order to eliminate water rationing and the supply calendar, it is also necessary to reduce water loss. Consequently, the level of water loss volume (LOSS) is considered an attribute to be minimized, for which the value is an expected index of the losses after the implementation of an alternative considered as the worst alternative for not contributing to the reduction of losses, maintaining it at the current 55% level.

There are two attributes related to the service provided to consumers. The first one is water availability (AVAI). Although it is clear that this variable is related to others, such as the volume of water entering the system and reduction of water loss volume, it is another essential measure for the operations manager because it reflects the quality of the service provided to the population, since increased water availability lessens damage caused by shortages. Therefore, 100% availability is the best scenario while 30% is the worst, which is the actual average availability in the sectors covering the region studied. The second consumer related service attribute is reduction in the number of expected complaints from clients (COMP) when it comes to water quality, leaks in the pipes, lack of water in scheduled days, and etc. Its scale varies from 1 to 7, where 1 means no reduction in complaints and 7 means almost no complaints. Hence, this is also a measure of the company’s image as far as the population is concerned. The other nominal attribute is applied to measure the degree of impact it has on the water company's image according to the public government and private investors (IMAG). Its scale has 7 levels, ranging from 1 with no-impact on the company's image to 7, having maximum impact leading to new investments.

Table 4 - Characterization of the attributes

Attribute	ID	Unit	Intent	Min	Max
Cost of implementation	COST	BRL mi	Minimize	0	135
Increase in water flow feeding the system	WFLO	m³/s	Maximize	0	1
Water loss index	LOSS	%	Minimize	15%	55%
Average of water availability for consumers	AVAI	hours/week	Maximize	30%	100%
Expected reduction in consumer complaints	COMP	Nominal	Maximize	1	7
Contribution to company's image	IMAG	Nominal	Maximize	1	7

Source: This research (2018)

3.3.3 Alternatives and its performances

The alternatives were created aiming to meet one or more objectives of the decision-maker, according to the procedure described in Section 3.2. It is no wonder that the VFT stands out in the creation of alternatives for problem structuring: note that as you move through objectives in an up-down direction, they become more and simpler, to the point where some of them may refer to an action or alternative by itself. This is the case of alternatives A1 to A9, but this does not exempt the study of how this alternative meets other objectives, since it is fundamental to define its performance within the attributes. In the cases of A10 and A11, these alternatives were created by analyzing the objectives network in which A10 was developed when talking about the causes of water losses and the investments to reduce the operations costs, and A11 was developed by combining the objectives of to promote the better us of the resources and increase the speed to solve urgencies, aiming to reduce both the water losses and the damage to population.

- A1: Register the non-clients consumers in order to reduce the water losses and consequently minimizing the operations costs. If these consumptions are recorded, the company's revenue also increases. For this alternative, it is possible to carry out a joint effort with government to incentive population, which may be developed with the alternative A2. This alternative does not causes increment in inlet water flow, but can bring a sensible reduction in water losses, associated with the estimated water diverted from pipelines. Approximately $ 2 mi can be applied to registration and routine inspection of irregular consumers, based on previous actions of water company.

- A2: Develop social and awareness programs regarding the conscious water consumption, involving schools and residents associations. This alternative is related to the better use of the water resources which contributes to reduction of water losses and to reduce the gap between supply and demand. It can also be associated with A1. Besides the direct contact with community, he suggested spread the programs in advertisement media and the creation of a mobile app to have a faster communication channel between water company and consumers.
- A3: Increase the number of specialized staff team aiming at reducing the time to solve the urgencies in the water system mainly network maneuvers and leak repairs. The alternative also includes qualification courses. According to the manager, almost double the number of current employees from company (not considering outsourced ones) is necessary to perform a good service. The related cost involves also the approximated cost of 3 vehicles and tools to equip the team.
- A4: Open new contracts with outsourced companies, solving the current debits, and reduce the bureaucracy when triggering their services, accelerating processes that require urgency, reducing the amount of water loss and improving the company's image. According the local manager, there are problems with two outsourced companies.
- A5: Increase the number of water network sectors. When the number of independent sectors is greater, less water is lost in the leaks and the impact to the population is smaller, since a smaller part of the network should to be interrupted for corrective intervention.
- A6: Replace old pipelines, since it has a great impact in water losses. Almost the whole extension of the Olinda's water network is more than 50 years old and was not designed for the current elevation in pressure.
- A7: Redesign the city's hydraulic system. This alternative is the most expensive, but the one that most contributes to improving water supply service, reducing water losses,

improving company's image and balancing supply and demand. It includes the projects of increasing the sectors quantity form 13 to 21, replacement of 60 km of water network for the long term, and the construction of 3 new reservoirs. Note that part of this alternative is related to A5 and A6.

- A8: Connect the local dam to other river basins. The hydrographic basin neighboring Botafogo dam has an extra capacity that could be harnessed, increasing the water provided to Olinda. This was a project already though and planned by water company in 2014, but it was not executed. Capibaribe River is 10 km far form Botafogo dam and its flow is sufficient to increment it.
- A9: Drill more wells in the region aiming increase the water production, as well as A8, although this alternative needs a geological study to evaluate the capacity of the groundwater sources. The data presented in Table 3.4 refers to drill 6 wells and connect them to water network.
- A10: Modernization of the measurement and control equipment. Replacing the equipment used to measure water flow can improve the system by reducing the water loss since one of its major causes is measurement errors. That will consequently lead to operation costs reduction. Automated equipment can also reduce the use of manpower and make the network operation faster.
- A11: Optimize maintenance activities. Although small, this alternative contributes to a reduction in water loss. Its main characteristic is low cost, as it involves only a study on maintenance activities and the reorganization of preventive maintenance schedules, which also optimizes routine operations resources.

The alternatives had their consequences described in terms of the attributes defined in the previous section, as showed in the consequences matrix (Table 5). The performances of the alternatives were defined from previous budgeted projects of the water supply company or estimated by the decision-maker.

Table 5 - Consequence matrix

Alternative	Performance					
	COST	**WFLO**	**LOSS**	**AVAI**	**COMP**	**IMAG**
A1 – Register non-clients consumers	2	0	48	30	1	5
A2 – Social and awareness programs	2	0	48	30	3	7
A3 – Increase the number of specialized staff	10	0	50	30	1	3
A4 – Solve problems with outsourced companies	0	0	50	35	1	2
A5 – Increase the number of water network sectors	50	0	21	55	5	5
A6 – Replace old pipelines	25	0	28	50	5	5
A7 – Redesign city hydraulic sstem	135	0	15	100	7	7
A8 – Connect Botafogo dam to other river basin	95	1	55	65	6	6
A9 – Drill more wells	3	0,3	55	50	4	4
A10 – Modernization of measurement and control equipment	10	0	38	45	2	4
A11 – Optimize maintenance activities	1	0	45	35	2	3

Source:This research (2018)

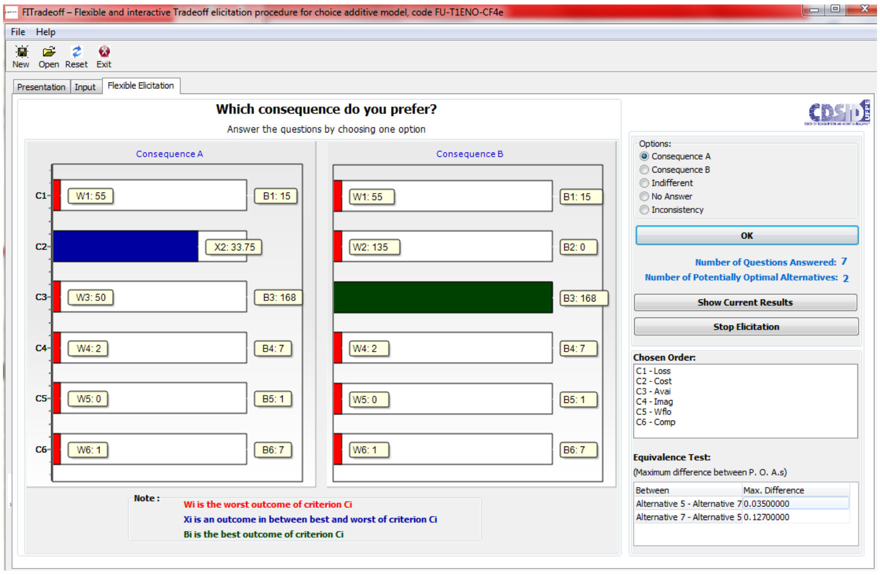
3.3.4 FITradeoff elicitation and recommendation

The first step of the procedure is the ordering of the attributes according to the decision-maker's preferences. The operations manager ranked them as follows: 1st LOSS, 2nd COST, 3rd AVAI, 4th IMAG, 5th WFLO and 6th COMP. After this step, the FITradeoff process required 8 interactions to reach a unique potentially optimal alternative for which questions are described in Table 6 along with its respective answers. Figure 8 is a print screen of the FITradeoff software for obtaining the attributes weights and the Figures 9 and 10 represent the weights set which maximizes the performance of the selected alternative.

According the decision-maker when explained this attribute ranking, "*the water losses is the biggest problem of the water system and because of this LOSS is the most important attribute, surpassing the importance of the alternative cost (COST). Increasing water intake into the system (WFLO) is important, but it is not a priority at the moment, since it is not rational to increase water production if we are throwing away more than half of it all! Availability of water to consumers is important to measure the quality of the provided service,* *but I think it is less important than LOSS and COST, but is more important than company image for the government*".

When asked why to consider consumers' complaints (COMP) as the least important attribute, he pointed out that "*consumers complaints are likely to reduce when more water is available. This is the main cause of complaints*". And then, he was asked if he should not remove this attribute due to its duplicity. He preferred to maintain it since "*there is not a single cause of complaints. We also receive a considerable number of calls due to water leakages although it is not enough to cause a supply interruption, for example. The delay to perform the services also causes many complaints, since consumers call back us regarding the same complaint that has not yet been solved*". Given this justification, the attribute COMP remains in the evaluation.

Figure 8 - *Applying FITradeoff*



Source: FITradeoff Software

Based on reported data, the best alternative is A7 - redesign the hydraulic system of Olinda. This alternative consists in the development and execution of a project to address the future demand for water in the city by exchanging most of the old pipes for new ones with new of larger diameter and constructed with material of greater resistance and durability. Even though this is an excellent alternative, its cost is a drawback as can be seen in the consequence matrix. However, this reservation can be balanced out by its benefits in other attributes.

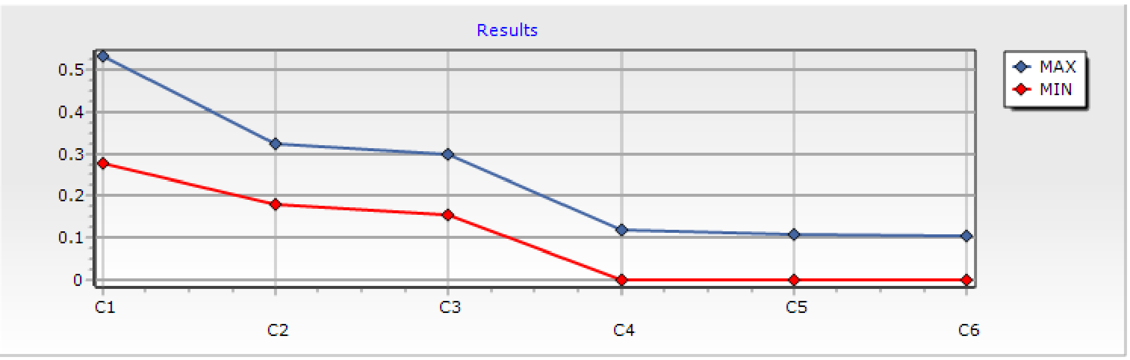
Table 6 - Steps of FITradeoff elicitation

Interactions	**Consequence A**	**Consequence B Maximum of**	**Choice**
1	35 of LOSS	COMP	A
2	35 of LOSS	COST	B
3	67.5 of COST	AVAI	B
4	109 of AVAI	IMAG	A
5	4 of IMAG	WFLO	B
6	0.5 of WFLO	COMP	B
7	25 of LOSS	COST	A
8	33.75 of COST	AVAI	B

Source: This research (2018)

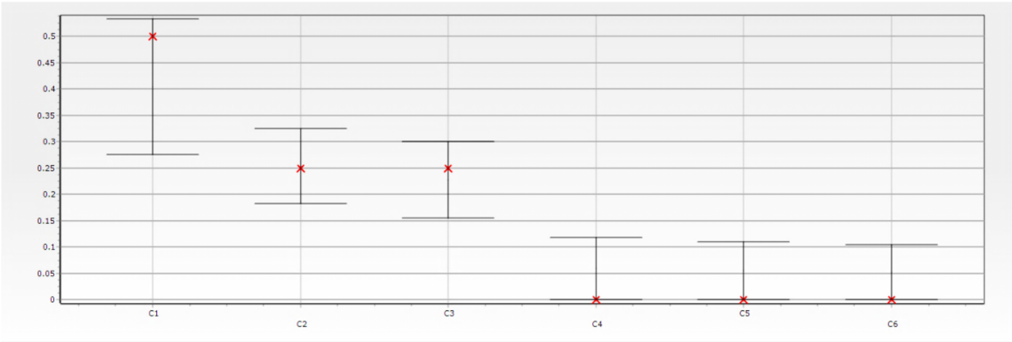
Therefore, the manager's choices lead to the optimization of the problem for the following range of scale constants for each attribute illustrated in figure 5 and as follows: C1 - LOSS, from 0.276 to 0.533; C2 – COST, from 0.182 to 0.324; C3 – AVAI, from 0.154 to 0.300; C4 – IMAG, from 0 to 0.119; C5 – WFLO, from 0 to 0.109; C6 – COMP, from 0 to 0.103. The result is a range because its FITradeoff is a partial information method. However, it guarantees that if a single solution is found it will dominates the other alternatives in any combination of scale constants inside the obtained set being, therefore, the optimal alternative (de Almeida et al., 2016).

Figure 9 - Attributes' scale constants space



Source: FITradeoff Software

Figure 10 - Weights for performance maximization of A7



Source: FITradeoff Software

The water loss reduction is an important objective as it is linked to most of the means objectives at lower levels and, from which, it is possible to reach the DM's two strategic objectives. This is a consequence of his great concern with the current water loss index, so the relates attribute (LOSS) is placed as the most important for DM.

3.3.5 Discussion and managerial implications

FITradeoff is a model that addresses the difficulties involved in making a choice, that is, the result of the methodology is a single solution. This methodology cannot be used for ranking alternatives since the scale constants may vary in the admissible weights space, which may cause alternatives order reversal, except for the first placed.

The proposed model supported the operations manager in making a better decision for the city of Olinda. Probably he would take much longer to think about all the case and the proposed model facilitated this task. The limitation of the model is its inability to solve problems that require a ranking of the alternatives.

The study allowed the operations manager to understand the system's characteristics. This model also provided ways of turning such characteristics into measurable variables, as well as, identifying restrictions in the problem which prevented achieving better system performance due to the limited number of staff and problems with subcontractor companies. So, the model has broadened the manager's mind on problems that he did not realize before.

Although the study was only carried out in operations management and the structure of the objectives is quite complex, it is in agreement with the strategic map of the company. This shows that there is a strong similarity between the expectations of the company and those of the operations department. Note that, although the operations department does not deal directly with the financial analysis of the company, it is concerned with achieving its goals, including it as a strategic objective.

This study also has a social impact since it involves the management of a commodity that is a constitutional right in Brazil. The social discrepancies become even clearer when considering that even in a small region different service profiles can be found and furthermore, it is correlated to the residents' social status. That actually put the water company in a tradeoff situation since it is forced to decrease service quality for the poorest sectors in order to achieve overall system efficiency. Hence, it is expected that the solution found in this study will eliminate that problem.

The decision-maker's objectives can be referred for further discussion with upper level management within company. This methodology can also be applied to other regions as well as to different decision-makers. Several objectives can likely be defined in the same way in other contexts since Olinda's water supply predicament is similar to that of other regions. In this manner, it is possible to determine a set of actions that improve the quality of the water supply service in the whole area managed by the company. Therefore, the objectives hierarchy is also useful when applied to the company's elaboration of strategic planning, thus enriching the vision of the enterprise with regards to the minutiae aspects of the business.

3.4 Chapter remarks

This chapter consists in a study of an urban water supply system which suffers with incapacity to supply all consumers in an acceptable level of service. Therefore, it is proposed a model for structuring the problem and finding an alternative considering the preferences of the water supply operations manager to deal with this complex situation. The application has implications in social and governmental contexts, but mainly to water system itself and to water company as the conditions under which the water supply system operates in the region may have great improvement.

The model consists in the integration of the Value-Focused Thinking and FITradeoff approaches, providing a complete model that supports the decision process from problem structuring, to recommending an alternative to the decision-maker. The goal of the model, particularly its FITradeoff feature, is to make use of decision support methods that are more feasible due to their ease of use, without compromising the quality of the results obtained when compared to traditional methods.

In this specific case, the results serve as a guide to direct future actions in the region studied, so that the operations managers and the company can achieve their goals. This result may be beneficial for both the company and the population they serve since this process will lead to better service quality. The results elucidate the operation of the water supply system, revealing areas in need of improvement which require actions from the company while showing the most urgent issues according to the operations management department. Finally, it suggests a solution that best meets the desires of the decision-maker when trying to solve the problems in question.

In a deeper analysis of this study, it may be noted that as well as in some papers presented in literature review, this is also a case that may require a group decision approach. It was something indicated by decision-maker when considering the appreciation of his own actions by other parties in his objectives structure. It was translated in terms of two separated attributes evaluated in a qualitative scale: the number of reclamations, which can be a proxy attribute to consumers satisfaction, and the company image, which actually is a consequence of evaluations by other stakeholders as government and investors. From this point of view, the case study deserves to be addressed considering the preferences of other individuals, which would later be aggregated to form an objectives structure for the group and seek a solution to satisfy the wishes of whole group.

Questions may arise from considering this group approach: what would be the opinion of the other individuals about this problem? What are their objectives, criteria and weights? Could more alternatives be created? Would individuals have the same degree of responsibility for this decision? The scope of this thesis is limited to the problem structuring with operations manager, therefore these questions are not answered here and being proposals for future work. In other words, it is proposed future applications of VFT and FITradeoff with representatives from others departments form water company, Pernambuco Government, regulatory agencies and consumers.

Although the problem structuring phase has not been performed with a group, in future works the preferences of the participants will have to be somehow aggregated to form the collective preference. It can be done from aggregation models that deal with the initial preferences of decision-maker or those which deal with their final choices. As we cannot anticipate initial preferences of the other individuals (objectives, criteria, scale constants), a proposal is to opt for studies on aggregation of final preferences, particularly Social Choice

Theory: it does not matter how decision-makers evaluate the alternatives set, but rather the result of this judgement.

Social Choice Theory is the subject of the next two chapters that will address the properties of voting procedures, evaluation of a model already existing in the literature with application in the context of water resources management and finally the development of a new model which enriches the aggregation process with more information and can also be applied in the described case study after obtaining individuals preferences profiles

4 A GROUP DECISION-MAKING MODEL FOR MAINTENANCE MANAGEMENT IN URBAN WATER SUPPLY

This chapter describes the development of a model to support group-decision making based on social choice theory to perform preventive maintenance planning in pumps for water distribution. Individual preferences were elicited with three decision-makers, one of them representing consumers and the others are maintenance managers of Water Company. This study reveals difficulties in water supply which commonly occurs in developing regions and changes in interval to perform maintenance intervention can reduce the damage to the population due to lack of water. After analyzing individuals' criteria to evaluate alternatives and the maintenance and breakage log, it is possible model their criteria from maintenance engineering models which enable us generating a complete ranking of alternatives, by applying a multicriteria model, and aggregating them by quartile-based voting.

This chapter also analyzes the characteristics of quartile-based voting proposed by Morais and de Almeida (2012). The paper where this methodology was initially proposed has application in the management of water resources. Morais and de Almeida (2010) presented the first version of this model in a situation with six alternatives and four decision-makers for choosing an action to rehabilitation of water network infrastructure. In a second publication, Morais and de Almeida (2012) applied the quartile-based voting for selection of an alternative to control the degradation of a hydrographic basin of a Brazilian river. They brought a deep description of the study case, raising the critical issues and the role of each stakeholder in this situation. Prior to the application of the voting method, each individual had his / her preference profile drawn from a multi-criteria decision aid model in order to avoid strategic voting. Although not required, this step is recommended (MORAIS; DE ALMEIDA, 2012). So the individual rankings were obtained through PROMETHEE II and after voting, the most suitable alternative was selected. Cunha and Morais (2015) presented the situation of the water crisis faced by the richest Brazilian region. This case considered six decision-makers to choose one alternative from a set of twelve. They showed that the quartile-based procedure is a good option to aggregate individual opinions, even divergent ones.

Many derivations from the Arrow conditions were created to deal with impossibility and Richelson (1978) shows that these studies led to the development of new methods. An important approach to social choice research is comparing procedures, characterizing them on the reasonable conditions they satisfy (RICHELSON, 1978; NURMI, 1983; PALHA, 2017). These conditions and their derivation were transformed into criteria, which were described in literature review Section. A motivation to carry out this analysis is that although quartile-based model has already been applied in other published works for the management of water resources, its properties have not yet been demonstrated in the literature. So, it is applied the data from the application of the voting model for maintenance management creating possible scenarios in order to support the demonstrations of model properties.

4.1 Problem context: maintenance management of pumps for water distribution

The case presented in this chapter addresses part of a water supply system in Recife city, which is capital of Pernambuco state. Plains areas of the city already has a continuous water supply, but in some hills areas the supply is even worse than observed in Olinda case since wells are the only source of water available for this region. This study in published in de Almeida-Filho et. al (2017).

Hilly regions compose the periphery of Recife, located approximately 8 km from the city center, and composed predominantly by low-income families in a high population density, around 28,000 inhabitants/km² (RECIFE, 2016). Urban planning did not keep pace population growth in these area and the peripheral areas suffer from deficiencies in provision of public services as occurs with water supply, which community constantly experience shortages of water. Although this study is limited to this region, this condition affects a great region in Recife Metropolitan Area and the entire wells system consist of about 190 wells.

In the hills neighborhoods, located in the Recife North, the water supply is carried out through deep wells which water is pumped directly into the distribution network. It supplies around 30,000 inhabitants and, although wells and equipment for water distribution work 24 hours a day, they have not capacity to supply all consumers simultaneously. So the region was divided into sectors, which are supplied according to the Water Company calendar, and each sector has an average of 24 hours per week of availability. Water rationing is a great clamor of the local population; therefore the availability criterion is used to define their preferences profile.

Regarding the water company, there is a contract with state government for providing water and sanitation services. Such contract stipulates that the company shall provide the distribution service in a regular, continuous and efficient manner. As to efficiency, the service must be performed at the lowest possible cost, in line with the standards set by regulatory agencies. Therefore, such agencies, which are part of the government, are also responsible for setting the fees charged for the water distribution service. The reasons that make it legal for the water delivery service to be interrupted are technical reasons or safety of the installations; improper handling of distribution networks and/or of equipment that are company owned; consumer debt with the company or a *force majeure* event. Such *force majeure* events should be justified with the regulatory company and include the regularly recurring problems in the region such as water scarcity and system failure.

The system failures are the focus of this study. All areas are subject to interruption in supply due to equipment breakdown, which may be broken pipes or defects in pumps or valves. In this study, only the failures in pumps are studied, as it is the most expensive item and presents the greater costs to perform maintenance and requires more time in its intervention, mainly because the pumps are submerged in the wells.

Since 2012, the maintenance policy is based on preventive maintenance, that is, maintenance services must be performed periodically in order to reduce the likelihood of a failure. In this way, the question arises: How often preventive maintenance should be performed? Moreover, considering that there is more than one manager responsible for wells management, how to deal with different opinion when defining the preventive maintenance plans? What happens if population opinion is considered in this technical decision-making problem? These questions can be answered by using a voting model which to aggregate preferences previously described through different multi-criteria decision-making models and maintenance engineering variables.

The mainly reason that the Recife North area was chosen is that the water network is linked only to wells, so its water supply is independent and does not vary according to operations condition of other regions in the city. The result obtained in this study cannot be directly applied to wells in other areas of the city because each area has its own characteristics which leads to consider different criteria to describe the system as well as with different degree of importance, besides the supply parameters as number of consumers, network pressure and different failures behavior of the wells. Nevertheless, the methodology can be replicated in other maintenance problems, obtaining the appropriate result to solve it.

4.2 Description of the model

4.2.1 Detailing maintenance problem and decision-makers preferences

First, it is necessary to evaluate the costs of performing periodic preventive maintenance and the costs they will incur in the event of an unscheduled breakage, as well as the time required to perform theses interventions (RAUSAND; HØYLAND, 2004). This evaluation includes the technical labor, vehicles, cables and equipment, the parts to be replaced, electricity, and the cost of not selling water (revenue that would enter the company in case the pump was in operational state). The preventive aims restoring the well so that it has the conditions of operation like a new one (RAUSAND; HØYLAND, 2004), performing its cleaning, and mechanical, electrical and hydraulic services. If a corrective maintenance is necessary, the submersible pump needs to be replaced.

Secondly, it is necessary to take account of the decision-maker criteria, because not necessarily the maintenance plan that minimizes the cost will be what maximizes the availability (JIANG; JI 2002). In addition, besides cost and availability, there are several criteria commonly considered in maintenance management: reliability, system interruption frequency, mean time between failures, mean time to repair, etc. The advantage of using these maintenance variables as criteria is that they can be described in terms of preventive maintenance interval, once this maintenance policy has been adopted.

After analysis with operations managers, it is verified that the time taken to perform a preventive maintenance is almost 5 times the time for a corrective maintenance and the ration between their costs can reach up to 120. By studying the history of pump failures and adjusting the data to the Weibull distribution, it was detected that failures are caused by aging. These information lead to conclude that performing preventive maintenance is in fact a possible solution to reduce the time and cost to perform maintenance (RAUSAND; HØYLAND, 2004).

For the local operations, there are two managers responsible to define the maintenance plans, who are the decision-makers of this case, each with a different perspective on this subject and consequently taking into account different criteria. The first decision-maker (DM1) is a senior engineer of Water Company and the chief of the maintenance department. He implemented the change in maintenance policy from acting correctively when breakages occur, to act proactively by performing preventive maintenances before occurrence of breakages. DM1 considers two criteria for evaluation of the consequences of his decisions for the region when planning the activities of maintenance sector: the cost of performing maintenances and availability of pump for water supply. Moreover, DM1 sees a compensation relationship between these two criteria, main reason for choosing MAUT.

The second decision-maker (DM2) is also an engineer employed by Water Company, that although is subordinate to DM1, his opinion is considered of equal importance. DM2 perspective is different since his duties involve him in dealing constantly with public responding their requests and daily scheduling activities. Therefore, he considers a different measurement of system performance, prioritizing the increase of its reliability and reducing the frequency at which the system fails by SAIFI (System Average Interruption Frequency Index). SAIFI is commonly adopted in management of electricity distribution and considers in its calculus the quantity of consumers affected by system interruption (MONTE; DE ALMEIDA-FILHO, 2015). DM2 also considers the cost of maintenance activities as a criterion and prefers to apply an outranking methodology since for him it is hard to think in a compensation relation mainly between criteria Reliability and SAIFI.

The third decision-maker (DM3) represents local population, which is not common in this type of decision, but adding your preference can bring very different and even more efficient results (OSTROM, 1990). He has little technical knowledge of how maintenance system operates. However, he would like to have a service that is as good as possible, considering the constraints of the system. Thus for DM3 the only aspect that should matter in this decision is the availability of the water system, thus reducing shortages in the supply of water. This is quite reasonable because, since the region suffers constant rationing, a few more hours of water being supplied would be a great benefit, thereby making residents' domestic routines less uncomfortable. Opinion of the population about provision of public services may diverge greatly, however for the studied case it is common knowledge that everyone want to increase water availability in their homes. Therefore, availability is a single criterion to represent their opinion.

For DM1 a suitable approach is Multi-attribute Utility Theory (MAUT), which is applied in accordance with the procedures provided by Keeney and Raiffa (1976). The reason for using this method is the identification of a compensatory rationing, who was assessed with regard to the tradeoff amongst criteria (DE ALMEIDA et al. 2016; KEENEY; RAIFFA 1976). For DM1, increasing cost is valid if there is a greater availability of the system for the population. Utility independence between criteria was verified, which allows the use of a multilinear multi-attribute utility function (KEENEY; RAIFFA, 1976). The next session shows how to describe his criteria in terms of preventive maintenance interval. So, based on resulting utility level of each alternative, they can be ordered in a ranking. For DM2, due to non-compensatory reasoning, PROMETHEE II (BRANS; MARESCHAL, 1984) was chosen to obtain his ranking. Simplicity and ease of understanding were points that contributed to choosing PROMETHEE II from among other outranking methods. In addition, as the problematic of this method is ordering, it will provide a ranking which is the input of the voting procedure. For DM3, as availability is the only relevant criterion, from the model that will be described in the next session it is possible to evaluate each alternative and order them.

4.2.2 Modeling criteria with maintenance engineering variables

As failures are caused by aging, preventive maintenance is a suitable policy to be applied with interventions performed on the pumps each τ time units in operation. This variable is defined as the interval between preventive maintenance activities. Equipment is subject to failure at any time and governed by a probability distribution function with a Weibull-shape parameter (β) greater than 1 (CASSADY; KUTANOGLU, 2005).

When applying preventive maintenance policy, the consequence is to be able to manipulate stochastic variable as availability, system reliability, frequency of downtimes, failure rate, cost of interventions, etc. (DE ALMEIDA et al., 2015). As the problem is to choosing a value of τ, these variables are described below in terms of τ, which also are criteria for DMs.

SAIFI is the acronym for the System Average Interruption Frequency Index, initially created by IEEE (2012) to measure the average number of interruptions to the electricity supply in a year, but broadly applicable. This is directly proportional to the failure rate λi and the proportion of consumers affected when there is a failure Si. In the case studied, the sectors are divided so that each sector has approximately the same number of customers. According to Li et al. (2003), the failure rate is the predominant factor in determining SAIFI, which is obtained by (4.1).

$$SAIFI_i = \lambda_i S_i \quad (4.1)$$

Failure behavior of equipment can be described by a two-parameter Weibull function (WEIBULL, 1951) with a parameter shape β greater than one. Failure rate λ steadily increases over time *t* and is written as (4.2). η is the scale parameter of Weibull function, also determined by fitting. In this situation, alternatives with shorter intervals between preventive maintenance actions have lower SAIFI levels, and also provide high levels of reliability.

$$\lambda(t) = \frac{\beta}{\eta}\left[\frac{t}{\eta}\right]^{\beta-1} \tag{4.2}$$

There is a direct relationship between SAIFI and reliability by failure rate function as described by 4.3, in which *f(t)* if the Weibull probability density function. SAIFI measurement includes the population affected by the occurrence of a failure. However, in many studies, the reliability of the equipment is considered as a criterion. Reliability can be used as a criterion depending on the convenience since it is a proxy for explaining the failure behavior of the equipment. Reliability is the probability that a piece of equipment does not fail until a specific time *t* (DE ALMEIDA ET AL. 2015), as in 4.4.

$$\lambda\ (t) = \frac{f(t)}{R(t)} \tag{4.3}$$

$$R(t) = e^{-\left({t}/{\eta}\right)^{\beta}} \tag{4.4}$$

Since reliability is the probability of the equipment not failing in 0 to t interval, 1 – R(t) means the probability of a failure occurring in this same interval, which is obtained from the history of equipment failure adjusted to an exponential regression model. An assumption of the model is that the age of the equipment returns to zero after each maintenance intervention, that is, it is considered that after a preventive maintenance the pump works "as good as new" (RAUSAND; HØYLAND, 2004). In water systems, pumps work 24 hours a day stopping only for maintenances activities (preventive and corrective, if necessary). Thus, there are three possible states for the pump: in operation, stopped for preventive maintenance taking approximately t_p hours, or stopped for corrective maintenance, which takes approximately t_c hours. According to Jiang and Ji (2002), availability can be describes as 4.5, which the highest possible value is desired. Note that A is a dimensionless measure, but multiplying *A* by a certain period *t*, the expected downtime of equipment can be obtained.

$$A(\tau) = \frac{\int_0^\tau R(t)dt}{\int_0^\tau R(t)dt + t_c F(\tau) + t_p R(\tau)} \qquad (4.5)$$

The managers of this case consider cost as a variable and they are in accordance with literature. Moreover, several papers also say that modelling maintenance cost must be associated with a time unit (BEICHELT, 1976; GLASSER, 1969; CHAREONSUK et al. 1997; DE ALMEIDA, 2012). In this study, cost per cycle K is measured in \$/hour, which should be minimized. The cost model uses the same age-based assumption of availability model (BARLOW; HUNTER, 1960) and must include all aspects of maintenance costs (staff, equipment, vehicles, consumable materials, unsold water, etc.) for defining the cost of each preventive intervention *Cp* and the cost of a corrective maintenance *C*c. These terms are considered in *K* formula (4.6) (JIANG; JI, 2002).

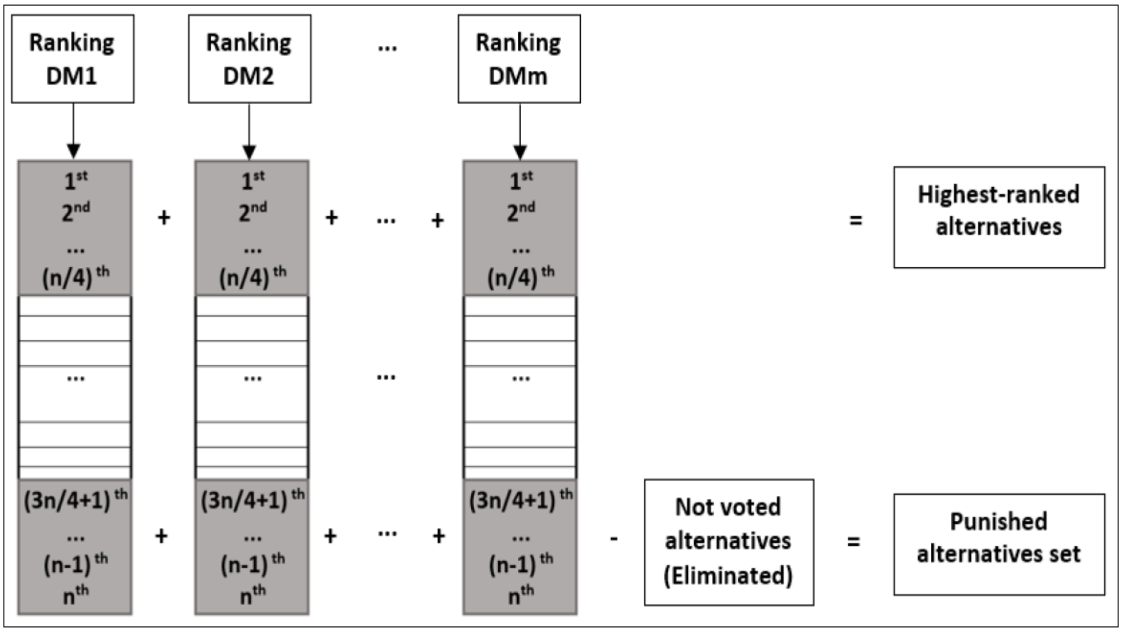
$$K(\tau) = \frac{C_c[1 - R(\tau)] + C_p R(\tau)}{\int_0^\tau R(t)dt} \qquad (4.6)$$

Optimization of each criterion equation provides different results for τ, thereby characterizing the problem as having conflicting goals even for only one DM. However, when performing the optimization, the limits of the decision space are defined. All alternatives must be within the interval defined by optimization and any alternative outside this is considered to be dominated, because its performance is lower in all criteria simultaneously. Thus, after setting the set of alternatives and quantifying them in terms of the criteria, a decision support method for each DM can be applied, the result of which is a ranking of alternatives. This is a necessary condition for aggregating the group’s preferences, which requires a ranking as input.

4.2.3 Quartile-based voting procedure

The input of this method, called quartile-based voting (MORAIS; DE ALMEIDA, 2012), is each DM's ranking of the alternatives. These rankings are divided into quartiles, where only the first and the last quartiles are analyzed as in Figure 11.

Figure 11 - Voting procedure scheme



Source: de Almeida-Filho et al. (2017)

The alternatives of the first group are strong candidates for the DMs to choose and they receive a score in accordance with their position in the ranking, resulting in its strength. However, those allocated within the last quartile are penalized, resulting in its weakness. Although the inputs are the individuals ranking, the models address only choice problems.

Each ranking is divided into quartiles but only the first and fourth are used, representing 50% of alternatives, while the alternatives allocated in the centrist positions are disregarded. Equation (4.7) is applied to obtain the position in the ranking which fits into the first quartile, where X must be rounded up and n is the number of alternatives. The lower quartile consists of alternatives that individuals voted below the position given by (4.8). The Y's value is truncated.

$$X = n/4 \tag{4.7}$$

$$Y = (3n/4) + 1 \tag{4.8}$$

Considering

$$q_{ij}^{k} = \begin{cases} 1, \text{ if the alternative } i \text{ is in position } j \text{ for the DM } k \\ 0, \text{ otherwise} \end{cases}$$

Thus, for the highest-ranked alternatives, calculate the strength (F) by Equation 4.9 and for those alternatives which must be penalized, calculate the weakness (f) by Equation 4.10.

$$F_i = \sum_{k=1}^{m} \sum_{j=1}^{X} (X - j + 1) q_{ij}^{k} \quad \forall i, k \;\; \forall j = 1, \dots, X \tag{4.9}$$

$$f_i = \sum_{k=1}^{m} \sum_{j=y}^{n} (j - Y + 1) q_{ij}^{k} \quad \forall i, k \;\; \forall j = Y, \dots, n \tag{4.10}$$

The score and penalty are given in a similar way to the Borda method (DE ALMEIDA-FILHO et al. 2017). This procedure must be followed for all DMs' rankings and the sum of points gained is computed, the result being the strength of the alternative. In the same way, the total of penalties received must be summed to calculate the weakness. For choosing the best alternative, consider the differences of the strength and weakness (α), as in (4.11). The alternative with the greatest α is the one chosen by the group.

$$\alpha_i = F_i - f_i \tag{4.11}$$

The model also allows vetoing alternatives in an additional step, evaluating whether there is a high disagreement about selecting an alternative. For an alternative *i*, if $f_i \geq F_i$, there is a strong opposition to this alternative and therefore it must be eliminated.

4.3 Results of applying the model

De Almeida-Filho et. al (2017) proposed the application of this method to establish a plan for preventive maintenance of pumps for water distribution in an urban Brazilian city. In this case, three decision-makers had their preferences elicited, one of whom representing the local population, which had their rankings obtained through different multi-criteria methodologies.

Managers kindly provided the records of past failures and interventions performed in the wells, enabling us to define the criteria functions. By optimizing these functions in terms of the preventive maintenance interval τ, it is possible to define the range of non-dominated solutions, which are ranging from 500 hours and 4000 hours. This range were divided into 15 values, corresponding to 15 alternatives, as the managers defined that 250 hours are sufficient to consider that these alternatives are not indifferent to each other. Table 7 presents the consequences matrix for the case.

Table 7 - Consequences matrix

Alternative	τ	**SAIFI**	**Availability**	**Cost ($/hour)**
A1	500	0.0533	0.991989	1.7464
A2	750	0.0914	0.994567	1.2835
A3	1000	0.1340	0.995828	1.1020
A4	1250	0.1803	0.996557	1.0368
A5	1500	0.2299	0.997018	1.0321
A6	1750	0.2822	0.997325	1.0635
A7	2000	0.3371	0.997534	1.1186
A8	2250	0.3942	0.997678	1.1900
A9	2500	0.4536	0.997775	1.2733
A10	2750	0.5149	0.997839	1.3652
A11	3000	0.5781	0.997878	1.4635
A12	3250	0.6431	0.997897	1.5665
A13	3500	0.6992	0.997902	1.6560
A14	3750	0.7780	0.997894	1.7812
A15	4000	0.8477	0.997878	1.8908

Source: de Almeida-Filho et al. (2018)

Equation 4.12 represents the elicited multi-attribute utility function for describing DM1 preferences (MONTE; DE ALMEIDA-FILHO, 2016) where *A* and *K* are the criteria functions of availability (4.5) and cost per cycle (4.6). Multi-attribute utility function was built using the traditional procedure described in Keeney and Raiffa (1976). Alternatives are ordered as per their utility level.

$$U = 72.9e^{-2285(1-A)} + 12.94e^{-3.65K} + 523.91e^{-(2285(1-A)+3.65K)} \tag{4.12}$$

DM2 presented the following parameters: reliability criteria, SAIFI and cost with weights 0.4; 0.4 and 0.2 respectively; U-shape function for all criteria and indifference threshold of 0.1 to reliability and SAIFI and 0.2 to cost. For the mono-criterion decision of DM3, the alternatives were ordered as per their expected level of availability, calculated from equation 4.5.

Table 8 presents the individuals' rankings of these 15 alternatives obtained through different in a different ways, defined according to the decision-makers reasoning: for DM1, the ranking was obtained considering an additive approach by applying Multi-attribute Utility Theory (MAUT); for DM2, the ranking was obtained considering PROMETHEE II methodology; and for DM3, the alternatives were ranked according their availability level.

Table 8 **-** *Individuals rankings*

Ranking	**DM1**	**DM2**	**DM3**
1	A12	A5	A13
2	A11	A6	A12
3	A13	A7	A14
4	A10	A4	A15
5	A14	A8	A11
6	A9	A3	A10
7	A15	A9	A9
8	A8	A2	A8
9	A7	A10	A7
10	A6	A11	A6
11	A5	A1	A5
12	A4	A12	A4
13	A3	A13	A3
14	A2	A14	A2
15	A1	A15	A1

Source: de Almeida-Filho et al. (2017)

As there are 15 alternatives, the first quartile is composed by the top four positions in the individuals rankings (15/4 = 3.75 → 4). The last quartile if composed by the alternatives from the 12th position ((3*15/4) + 1 = 12.25 → 12). Based on this, Table 4.2 presents strengths and weaknesses of the alternatives calculated from equations 4.3 and 4.4. Note that some alternatives are not shown in Table 9 since they were not allocated in the first quartile for any individual.

Table 9 - Alternatives strengths and weaknesses

Alternative	First quartile				Last quartile			
	DM1	DM2	DM3	Strength	DM1	DM2	DM3	Weakness
A4	1	0	0	1	0	1	1	2
A5	4	0	0	4	-	-	-	-
A6	3	0	0	3	-	-	-	-
A7	2	0	0	2	-	-	-	-
A10	0	1	0	1	-	-	-	-
A11	0	3	0	3	-	-	-	-
A12	0	4	3	7	1	0	0	1
A13	0	2	4	6	2	0	0	2
A14	0	0	2	2	3	0	0	3
A15	0	0	1	1	4	0	0	4

Source: de Almeida-Filho et al. (2017)

Alternatives which weakness is greater than their strength must be eliminated (MORAIS; DE ALMEIDA, 2012), which occurs for A4, A14 and A15. So, the remaining candidates are potential candidates to be chosen. Table 10 presents the intensity of strength of the alternatives, calculated by equation 4.5, providing the one which best represent the common view for this case.

Table 10 - The choice phase

Alternative	Strength	Weakness	Intensity
A12	7	1	6
A5	4	0	4
A13	6	2	4
A6	3	0	3
A11	3	0	3
A7	2	0	2
A10	1	0	1

Source: de Almeida-Filho et al. (2017)

Thus, A12 is the winner alternative, as it is the strongest one and with little objection. Note that A5 and A13 are also good candidates, as they were the first placed alternatives for DM1 and DM3.

4.3.1 Sensibility analysis on decision-makers' weights

Simulation of various scenarios is an important tool in decision analysis because brings a good understanding of the problem as it facilitates the visualization of the results against variations in parameters, such as the DMs weights. Thus, allows to evaluate the consistency degree of the chosen alternative and to know in which situations the result may differ. This analysis is proposed in this text from DM weighting in the voting procedure and evaluating the consequent scenarios generated by its possible orderings.

Generally, assignment of weights/importance degree to DMs is a difficulty found in group decision problems. In our study case, there is a senior engineer (DM1), to whom naturally one may give more importance, but he is not comfortable to attribute himself a higher weight and he preferred all DMs have equal contribution to this decision. So, in the original problem DM1, DM2 and DM3 have equal weights, however the case has motivated the study of the behavior of this process if different weights were assigned. Thus the results were calculated face to various combinations of weights, which were compared with the results of the original problem.

Table 11 presents the description of six scenarios created by attributing weights to decision-makers. In order to simplify the analysis, the weights set is (0.5, 0.3, 0.2), so these six scenarios encompass all possible combinations of attributing these weights to the three decision-makers. This analysis is published in (MONTE et. al, 2016).

Table 11: Scenarios of weighs sensibility analysis

Scenario		**Weights**			**Winner**
		DM1	**DM2**	**DM3**	
1	DM1 > DM2 > DM3	0.5	0.3	0.2	A12
2	DM1 > DM3 > DM2	0.5	0.2	0.3	A12
3	DM2 > DM1 > DM3	0.3	0.5	0.2	A5
4	DM2 > DM3 > DM1	0.2	0.5	03	A5
5	DM3 > DM1 > DM2	0.3	0.2	0.5	A12
6	DM3 > DM2 > DM1	0.2	0.3	0.5	A12

Source: Monte et al. (2016)

From Table 4.5, there is a frequency of 4 situations where the winner is A12 (66,7%) and the other two choosing A5 (33,3%). So, the alternative from the original problem is the most frequent. A12 and A5 are the best alternatives for DM1 and DM2, respectively and the situations where A5 is chosen happen only when DM2 is considered the most important DM. It is noteworthy that even in situations 5 and 6, which have DM3 as most important DM, his preferred alternative is not chosen. A13 is the winner only if DM3 weight is much higher than the others. Actually, it is necessary that DM3 weight is at least 2.6 times greater than the weight of second DM if it is DM1 or at least 2.3 times greater than second DM weight if it is DM2.

4.4 Discussion

If the individuals applied the plurality model in this case, the result would be a tie between the three top alternatives, so quartile-based method performs better for this case. The same alternative is chosen is case of applying Borda’s and Condorcet’s procedure, consequently A12 is also chosen by Copeland, as it elects Condorcet-winner.

If the alternative A12 is implemented, the preventive maintenance should to be performed every 3250 hours (135 days). Thus, the expected consequences of this policy is a 20.1% maximum probability of pump breaking before the next preventive intervention occurs; an average interruption index of 0.688, which corresponds to an expected failure of $1.6(10^{-4})$ for 4300 people affected by an failure per sector; an estimated maintenance cost (preventive + corrective) of $13,700 per year; and only 18.4 hours downtime per year, considering just the pump maintenances (unavailability due to failures in the water distribution network is not considered)

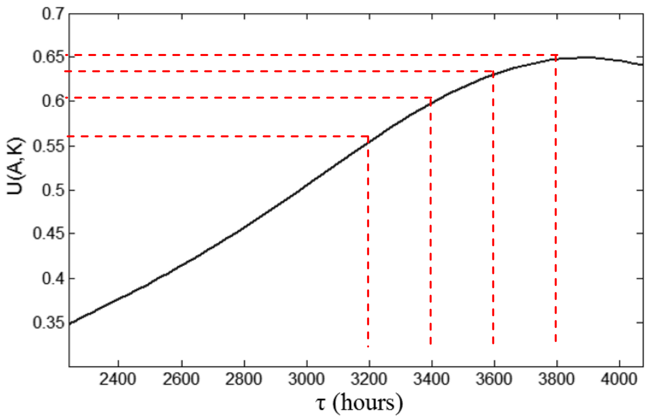
The effect of the participation of a representative of the population in this decision is also verified, even though it has been simulated. If the DM3 preference profile was not considered, the chosen alternative from the DM1 and DM2 rankings would be A5. This alternative represents a much smaller performance precisely in the criterion of availability, which was considered to describe the consumers' wishes. Thus, this shows the impact that can occur in the decision-making processes when considering the opinion of the population on issues involving the provision of public services, as the interests of managers and the population may diverge.

This application shows the advantage of the voting procedure by allowing different multi-criteria methodologies to obtain the alternatives ranking and reducing the alternatives set to focus only in important alternatives. However, it does not allow decision-makers consider the degree of desirability of alternatives in their statements. Decision-makers are required to provide a complete order of alternatives, not giving information on how much one alternative is better/worse than another, moreover does not allow them to attest if they are indifferent between two alternatives.

In quartile-based voting procedure and in others voting procedure as Borda’s counting, the function that attributes scores to alternatives is linear. Although their methodologies are based on ordinal scale (alternatives ranking), their scores are cardinal since alternatives scores are summed to obtain their group performance and a high position in a ranking of one decision-maker can be compensated with a low position for another decision-maker. This means that even if preferences of individuals are elicited from multi-criteria decision-making models, the input of such methods does not support all information about their preferences and any degree of preference between alternatives is not considered in group evaluation.

Note that in the case of DM1, whose preferences were elicited through MAUT methodology, the multi-attribute utility function is not linear as can be seen by the curve plotted in Figure 12. Considering τ = 3200 being an alternative for the case, an increase of 200 hours in preventive maintenance interval produces an increase of almost 0.05 in utility units. However, the same increase of 200 hours from τ = 3600 to τ = 3800 produces approximately half of the increase in utility verified in previous situation. This information is not considered in cited voting procedures. It is emphasized that the same does not occurs with preference elicited from DM2, since outranking flows obtained from PROMETHEE II do not mean the degree of desirability for an alternative.

Figure 12 - Utility function for DM1



Source: This research (2018)

In other words, the voting procedure may be aggregating preferences profiles that are not actually describing the will of individuals. Therefore, this situation is a motivation for the development of a voting method that considers such preferential cardinality over alternatives.

4.4.1 Model Properties for aggregation of group preferences

From the previously defined properties (Section 2.3.1), analysis of the quartile-based voting method can be performed. Although the rankings of the alternatives after aggregation, without veto, are presented in the tables of this section, it is emphasized that the Morais and de Almeida (2012) method is proposed for the problem of choice, and the presentation of the final ranking serves only for comparative analysis purposes. The analysis of method properties is useful for comparing methods and to know in which situations each procedure is recommended.

Property 1: Quartile-based voting is not a Condorcet winner method

Proof: It can be proved with a counter-example based in de Almeida-Filho et al. (2017) data with a little modification in A5 position, considering three (N = 3) decision-makers and fifteen alternatives (A = {A1, A2, ..., A15}) as in Table 12. Alternative A12 is a Condorcet winner, but it is not elected by quartile-based voting, which chooses A5.

Table 12: The choice of a non-Condorcet winner

	DM1	**DM2**	**DM3**		**Ranking – quartile-based voting**	**Ranking – Condorcet method**
1	A12	A5	A13		**A5**	**A12**
2	A11	A6	A12		A12	A5
3	A5	A7	A5		A6, A11, A13	A11
4	A13	A4	A14		A7	A13
5	A10	A8	A15		A8, A9, A10	A10
6	A14	A3	A11		A4	A14
7	A9	A9	A10		A14	A9
8	A15	A2	A9		A3, A15	A15
9	A8	A10	A8		A2	A8
10	A7	A11	A7		A1	A7
11	A6	A1	A6			A6
12	A4	A12	A4			A4
13	A3	A13	A3			A3
14	A2	A14	A2			A2
15	A1	A15	A1			A1

Source: This research (2018)

Property 2: Quartile-based voting obeys Condorcet loser criterion.

Proof: Consider Ax and Ay two alternatives from the alternatives set A and a group of N individuals. If Ax loses Ay in pairwise comparison, more than a half of the individuals (N/2 truncated) put Ax in a lower position of the ranking than Ay position. Considering that Ax is a Condorcet loser, this situation occurs with Ax when it is compared with all other alternatives in A. The highest score a Condorcet loser alternative could receive in Morais and de Almeida (2012) procedure would be to be first placed to (N/2-1 rounded up) individuals. In order to maintain the Condorcet loser condition, Ax must necessarily be allocated in the last positions for the other (N/2+1 truncated) individuals, consequently getting a higher weakness than its strength and being eliminated from the ballot. Therefore, a Condorcet loser can never be chosen by quartile-based voting.

Property 3: Quartile-based voting is monotonic

Proof: If an alternative Ax is the winner, the difference between its strengths and weaknesses is greater than this difference for any other alternative in the set. According to the scoring formula of the method, when the Ax is placed in a superior position in a ranking, there are three distinct situations: 1) Ax has its strength increased, if it is placed in the first quartile; 2) Ax score remains the same, if it is placed in the intermediate quartiles; or 3) Ax has its weakness reduced, if it is placed in the last quartile. Under neither of these situations it is possible to achieve a reduction in the Ax score. In addition, increasing its position also implies in reducing the score of other alternatives. Thus, raising the position of an already winner alternative will never imply in its disfavor, in other words, it remains victorious.

Property 4: Quartile-based voting obeys the Pareto-optimality criterion.

Proof: If Ax > Ay for the whole individuals, the score of Ay will never overcome the score of Ax. The worst situation is a tie between them, where both alternatives are placed in the intermediate quartiles and therefore it does not count points in its favor or to its disadvantage and Ay will never be chosen.

Property 5: Quartile-based voting is dependent of irrelevant alternatives.

Proof: The method is sensible to the number of alternatives contained in the set. If there is a subset of alternatives A’ from A, it contains less alternatives than the entire set A and the modifications in the scores are significantly different leading to choose different. Table 13 shows their original alternatives set and the individuals ranking of fifteen alternatives A = {A1, A2, ..., A15} and considers a subset of A, composed by A’ = {A1, A2, A3, A4, A5, A7, A12}, considering the same preferences profiles of the individuals. For the set A, applying the method A12 is the chosen, while the same does not occur by applying the method in A’.

Property 6: Quartile-based voting does not satisfy Chernoff condition.

Proof: The same of Property 5.

Property 7: Quartile-based voting does not satisfy the path independence condition

Proof: From Table 13: if all alternatives are considered simultaneously, A12 is chosen. But by considering just the winner of the subset A' for evaluation facing the remaining alternatives (the complement of A' to A), automatically A12 is eliminated even being part of A'.

Table 13: Application in a subset

	Set A					**Set A'**			
	DM1	**DM2**	**DM3**	**Ranking**		**DM1**	**DM2**	**DM3**	**Ranking**
1	A12	A5	A13	**A12**		A12	A5	A12	**A7**
2	A11	A6	A12	A5, A13		A7	A7	A7	A5, A12
3	A13	A7	A14	A6, A11		A5	A4	A5	A3, A4
4	A10	A4	A15	A7		A4	A3	A4	A2
5	A14	A8	A11	A10		A3	A2	A3	A1
6	A9	A3	A10	A8, A9		A2	A1	A2	
7	A15	A9	A9	A4, A14		A1	A12	A1	
8	A8	A2	A8	A15					
9	A7	A10	A7	A3					
10	A6	A11	A6	A2					
11	A5	A1	A5	A1					
12	A4	A12	A4						
13	A3	A13	A3						
14	A2	A14	A2						
15	A1	A15	A1						

Source: This research (2018)

Property 8: Quartile-based voting is consistent.

Proof: Consider two groups of individuals *G1* and *G2*, to which the procedure is applied over a set of alternatives *A*, resulting in choosing Ax for both groups. Considering that the preferences of each individual is independent of other individuals' preferences as well as of the number of individuals in the group. If the participants of *G1* and *G2* now composes a single group *G* to which the procedure is applied again, and their preferences profiles remains the same, the differences between strengths and weaknesses of all alternative in *G* are equal to the sum of this difference obtained in *G1* and *G2*. If Ax has the greatest score for both groups, their scores sum is also the greatest, so the result should be no other than A_x.

Property 9: Quartile-based voting is not vulnerable to no-show paradox.

Proof: Since the global score of an alternative is obtained by summing individuals' scores, there is no other way to benefit the desired alternative than voting in it.

Property 10: Quartile-based voting is simple

Proof: Each individual presents their preferences profiles (alternatives ranking) in just one balloting phase. So it is a “one-stage method”.

Property 11: Quartile-based voting is not easy to apply.

Proof: it occurs due to the definition of an easy method, which is a method based on just dichotomous information. Quartile-based requires a full ranking of alternatives.

The reason for this procedure to present dependence of irrelevant alternatives is the scoring function which depends on the number of alternatives. It can be seen in Equation 4.6, built by merging Equations 4.1 and 4.3. Since strengths and weaknesses are function of *N*, the insertion or removal of an alternative changes the whole scoring system.

$$F_i = \sum_{k=1}^{m} \sum_{j=1}^{X} [(N/4) - j + 1] q_{ij}^{k} \quad \forall i, k \ \forall j = 1, \ldots, X \tag{4.6}$$

If the changes in the size of alternatives set are made without changing the number of alternatives evaluated by the method (first and last quartiles), the effect of dependence of irrelevant alternatives can be reduced. However this assertion is only true if the inserted or removed alternative is evaluated in the intermediaries quartiles by all individuals. In other words, if alternatives are included or removed but the individuals decide to maintain the size of the alternatives sets which will be scored, and all individuals judge that the alternatives inserted/removed are in the second or third quartiles, the alternatives scores remains the same of the original situation.

If one decides to apply the Morais and Almeida (2012) counting of strength and weakness for the whole alternatives set (without eliminating the intermediaries’ quartiles), the procedure elects the Borda winner. This analysis is summarized in Table 14, based on Nurmi (1983), to which it is included the quartile-based voting. In Table 14, it is possible to see that quartile-based has the same properties of Borda counting. Although both present dependence of relevant alternatives, this effect is reduced in quartile-based procedure, since half of alternatives of the ranking of each individual are not accounted in preferences aggregation.

Table 14: Voting methods evaluations according various criteria

Procedure	**Condorcet Criteria**		**Rationality criteria**					**Implementation criteria**	
	C-winner	**C-loser**	**Monoticity**	**Pareto**	**WARP**	**Path indep.**	**Consistency**	**Simplicity**	**Easiness**
Binary									
Simple majority	1	1	1	0	0	0	0	0	1
Copeland	1	1	1	1	0	0	0	0	1
Dodgson	1	0	1	1	0	0	0	1	0
Schwartz	1	1	1	0	0	0	0	0	1
Maximin	1	0	1	1	0	0	0	0	1
One-stage									
Plurality	0	0	1	1	1	0	1	1	1
Borda	0	1	1	1	0	0	1	1	0
Approval voting	0	0	1	1	1	1	1	1	1
Quartile-based	**0**	**1**	**1**	**1**	**0**	**0**	**1**	**1**	**0**
Multi-stage non binary									
Black	1	1	1	1	0	0	0	1	0
Plurality runoff	0	1	0	1	0	0	0	1	1
Nanson	1	1	0	1	0	0	0	1	0
Hare	0	1	0	1	0	0	0	1	0
Coombs	0	1	0	1	0	0	0	1	0

1 indicates that a procedure meets a criterion, while 0 means that it does not meet.

Source: Adapted from Nurmi (1983)

4.5 Chapter remarks

A voting model was developed in context in the maintenance management of equipment for the water supply in the city of Recife. The application of the model in this context had as an advantage capturing the different ways of thinking about the case, allowing each decision-maker to evaluate the alternatives through criteria that they consider pertinent, as well as to apply the multicriteria decision aid model which is most adequate to their reasoning. The use of multicriteria models, as well as the description of the criteria with reliability and maintenance engineering models, avoids strategic voting, if it were the interest of some part. The aggregation of preferences has resulted in an alternative which is the better compromise between their divergent opinions, and it has been further shown that consideration of public opinion in decisions about the provision of public services can lead to quite different results.

Furthermore, it presented the analysis of the quartile-based voting proposed by Morais and de Almeida (2012). It is verified that Morais and de Almeida (2012) method is more suitable when applied in situations where it is not intended to make change to the alternatives set, as it presents dependence of irrelevant alternatives as a drawback. Once the method penalizes the last alternatives, an individual may vote dishonestly, issuing a preference profile that purposely prejudices other alternatives. Therefore, aiming to circumvent these occasions, Morais and de Almeida (2012) advocate the use of Multi-criteria decision aid methods. Moreover, the quartile-based method is consistent and simple to apply.

Despite the many positive features of the model, it does not consider the intensity of preferences between alternatives. Although its input is a ranking of the alternatives, it is not possible to know how much better one alternative is in relation to the others. Thus, since this information is not included during the group decision-making process, in some situations the result of aggregating individual preference profiles may not reflect the collective preferences. In addition, the Morais and de Almeida (2012) method deals only with the problem of choice since it can generate incomplete rankings due to elimination of alternatives.

So, what if individuals need a model to deal with ranking problems in groups? What if there are tied alternatives in their individual rankings? What if the group wants to consider their degree of preferences over alternatives? In relation to these aspects, it is proposed the model which is addressed in the next chapter: a model which aggregate individuals' preferences profiles considering intensity of preferences.

5 A VOTING MODEL CONSIDERING INTENSITY OF PREFERENCE

Traditional methods consider as input either just a single choice from each individual, a full ranking of alternatives, or require pairwise comparisons between alternatives (COOPER; ZILLANTE, 2012). These elicitations provide only poor partial information about individuals' preference and may not represent their real desire (GARCÍA-LAPRESTA; LLAZAMARES, 2010). Consequently, the result of the aggregation may not satisfy the collective will. The more information collected in this decision process, the more trustworthy the result, but it should not make the method unfeasible. One proposal is to consider the preference intensity of individuals over the alternatives set (VARGAS, 2016).

Therefore, various measurement scales were introduced for social choice theory (MUNDA 2012) such as the concept of fuzzy preferences (NURMI, 2008). With fuzzy preferences, individuals can express their preferences in degrees by values within an interval, in which the theories for the aggregation of fuzzy preferences are based on (BARRET et al. 1990), even though Dutta (1987) showed that this type of aggregation may produce a dictatorial result. Another strong approach considering preference intensity is linguistic scales from which several methods were derived (GARCÍA-LAPRESTA; LLAZAMARES, 2010).

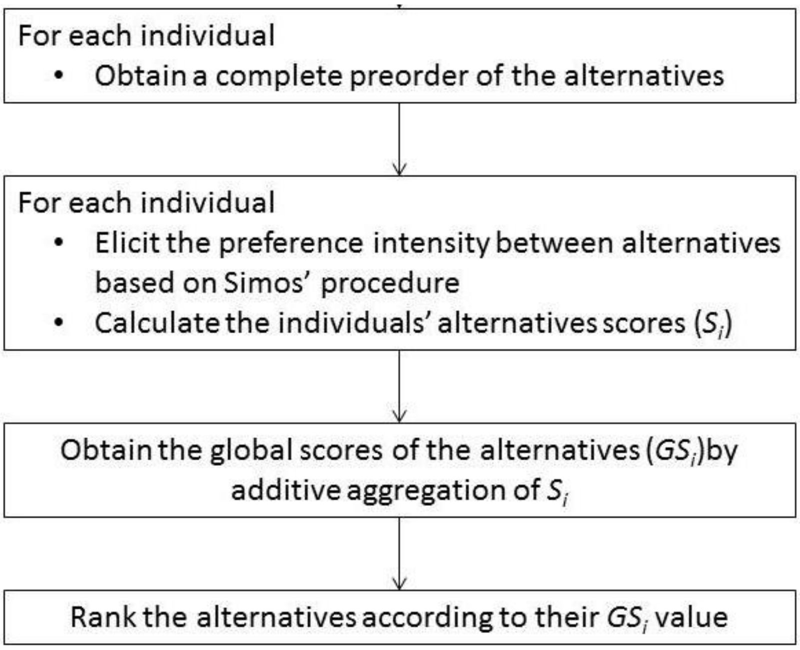
This chapter presents a model for aggregating individuals' rankings in a voting procedure that considers the intensity of their preferences on the evaluation of alternatives. Comparing with other methods with this feature, our proposal requires less effort from decision-makers. In addition, it gives freedom for each decision-maker to choose a multi-criteria decision-making method which is more suitable to his reasoning.

Evaluation is based on the Simos procedure, so differences between performances of alternatives are elicited no matter the criteria each decision maker/individual considers to evaluate them, followed by an additive aggregation. It is performed a simulation with a sensibility analysis and then the procedure was evaluated in terms of the Condorcet criteria, rationality criteria, and its easiness and simplicity for implementation. So, the context of chapter three is considered to base an illustration of the proposed methodology within the context of managing water resources.

5.1 Voting procedure with preference intensity

Since all individuals of group $G = \{D_1, D_2, \ldots, D_n\}$ can perform an exhaustive judgment on the alternatives of the set $A = \{A_1, A_2, \ldots, A_m\}$, their preferences can be elicited through the adaptation of the Simos Procedure (FIGUEIRA; ROY, 2002) for evaluating alternatives instead of criteria (FONTANA et al., 2011). In summary, each individual should provide a complete preorder of the alternatives, no matter the method applied to obtain it. Then, they are asked to insert white cards between the alternatives representing the differences between the performances of the alternatives according to their own preferences. A facilitator computes the scores of each alternative from each individual and performs the aggregation of their preferences, resulting is a ranking of the alternatives for the group. The framework in Figure 13 represents the structure of the proposed model. The details of the model and its characteristics are described in the following sections.

Figure 13 - Model framework



Source: This research (2018)

The facilitator gives a set of cards to an individual. This set contains m cards, which refer to the m alternatives from the set $A = \{A_1, A_2, ..., A_m\}$. Each individual should order these cards representing the ranking of alternatives from the worst to the best. If an individual considers two or more alternatives tied, s/he can put them in the same level, which will have the same scores at the end of the evaluation.

Each individual should insert white cards between the alternatives cards. Each white card represents a preference unit, denoted by u, and the more white cards between two alternatives or levels, the greater the difference between them. If the number of white cards between A_x and A_y is zero, the difference in preference intensity between A_x and A_y is equivalent to *u*; if there is 1 white card, this difference is two times *u*; and so on (FIGUEIRA; ROY, 2002; FONTANA et al., 2011). Therefore, the result of this "playing cards" step is the organization of the cards in levels: one is filled with one or more alternatives' cards representing the alternatives receiving the same punctuation; or they are filled with one or more white cards representing the difference in preference intensity between two levels of alternatives.

Specifically, *u* can be obtained by Eq. 5.1 (FIGUEIRA; ROY, 2002; FONTANA et al., 2011).

$$u = \frac{Z - 1}{K} \quad (5.1)$$

Where *K* is the number of white cards plus the number of levels filled with alternatives' cards minus one; and *Z* is the ratio between the evaluations of the best and the worst alternatives. *Z* is equivalent to the total number of cards *T*. But, if there are *a* alternatives in the most important level and *b* alternatives in the least important level, *Z* is calculated by Eq. 5.2 (FIGUEIRA; ROY, 2002; FONTANA et al., 2011).

$$Z = \frac{\left(\sum_{i=0}^{a-1}(T - i)\right)b}{\left(\sum_{i=0}^{b-1}(1 + i)\right)a} \quad (5.2)$$

For computing the scores S_i attributed to each alternative belonging to level *i*, consider N_i as the number of cards in *i* and each card must sequentially receive a *r-value*, which refers to its position in the ranking. The *r-value* is also counted for white cards.

The sum of the *r-values* from the same level *i* is called r_i. Thus, the non-normalized scores S_i' are given by ${r_i}/{N_i}$. The score is normalized by considering the sum of all r_i just for the levels filled with alternatives' cards ($\sum r_i^*$), resulting in S_i according to Eq. 5.3.

$$S_i = \frac{{r_i}/{N_i}}{\sum r_i^*} * 100 \quad (5.\ 3)$$

After computing the individuals' evaluations by Eq. 3, each alternative A_m has a score from each individual n, namely $S_{A_m}^{n}$. Therefore, the group score of A_m (GS_{Am}) is the sum of the individuals' scores, as in Eq. 5.4.

$$GS_{A_m} = S_{A_m}^{1} + S_{A_m}^{2} \dots + S_{A_m}^{n} \quad (5.4)$$

If the treated problematic is choosing an alternative, the selected is one with the highest value of GS_{A_m}. However, if the treated problem is ranking alternatives, it is done by considering the descending order of GS_{A_m}. Since scores are applied to evaluate the alternatives set, this voting procedure can also be called of a Social Choice Scoring Function (YOUNG, 1975).

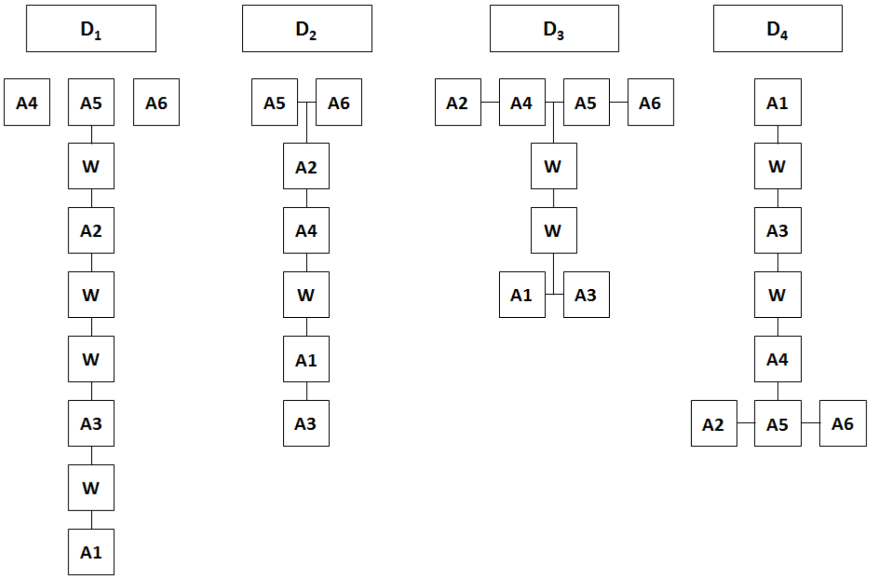
The Simos Procedure for criteria and alternatives evaluation (FIGUEIRA; ROY, 2002; FONTANA et al., 2011) has a problem regarding rounding off the scores to integers, which sometimes does not sum 100. So, more steps are required in a rounding off technique and scores correction. In our proposal to aggregation of preferences, the obtained scores are sufficient for the purpose of alternatives evaluation, and consequently avoiding the rounding off steps, making the application of the proposed method more feasible.

5.2 Simulations of group decision problems

5.2.1 Simulation 1

The simulation 1 was performed with a set of six alternatives $A = \{A_1, A_2, A_3, A_4, A_5, A_6\}$ and a group of four individuals, $G = \{D_1, D_2, D_3, D_4\}$. Thus the 'playing cards' of each individual was considered the same as those performed by (DM_1, DM_2, DM_{17}, and DM_{38}) in (KADZIŃSKI, 2018), who judged criteria for insulating material evaluation. Figure 14 is the evaluation of the selected individuals in which the symbol '*W*' in a card represents that it is a white card.

Figure 14 - Representation of individuals' preference through cards



Source: This research (2018)

According to their choices, Tables 15 – 18 were built to compute the scores (S_i) attributed to each alternative by the individuals, calculating through Eq. 3. The global scores of the alternatives are obtained by Eq. 4, from which the final ranking is obtained as in Table 19.

Table 15 - Obtaining scores for D_1

Level	**Cards**	**N_i**	**r-value**	**S_i'**	**S_i**		**Alternatives scores**	
1	A_1	1	1	1	2.703		A_1	2.703
2	White	1	2	-	-		A_2	16.216
3	A_3	1	3	3	8.108		A_3	8.108
4	White White	2	4 5	-	-		A_4 A_5	24.324 24.324
5	A_2	1	6	6	16.216		A_6	24.324
6	White	1	7	-	-			
7	A_4, A_5, A_6	3	8, 9, 10	9	24.324			
			$\sum r_i^* = 37$					

Source: This research (2018)

Table 16 - Obtaining scores for D_2

Level	**Cards**	**N_i**	**r-value**	**S_i'**	**S_i**		**Alternatives scores**	
1	A_3	1	1	1	4.0		A_1	8.000
2	A_1	1	2	2	8.0		A_2	20.000
3	White	1	3	-	-		A_3	4.000
4	A_4	1	4	4	16.0		A_4	16.000
5	A_2	1	5	5	20.0		A_5	26.000
6	A_5, A_6	2	6, 7	6.5	26.0		A_6	26.000
			$\sum r_i^* = 25$					

Source: This research (2018)

Table 17 - Obtaining scores for D_3

Level	Cards	N_i	r-value	S_i'	S_i		Alternatives scores	
1	A_1, A_3	2	1, 2	1.5	5.172		A_1	5.172
2	White White	2	3 4	-	-		A_2	22.414
							A_3	5.172
3	A_2, A_4, A_5, A_6	4	5, 6, 7, 8	6.5	22.414		A_4	22.414
			$\sum r_i^* = 29$				A_5	22.414
							A_6	22.414

Source: This research (2018)

Table 18 - Obtaining scores for D_4

Level	Cards	N_i	r-value	S_i'	S_i		Alternatives' scores	
1	A_2, A_5, A_6	3	1, 2, 3	2	8.333		A_1	33.333
2	A_4	1	4	4	16.667		A_2	8.333
3	White	1	5	-	-		A_3	25.000
4	A_3	1	6	6	25.0		A_4	16.667
5	White	1	7	-	-		A_5	8.333
6	A_1	1	8	8	33.333		A_6	8.333
			$\sum r_i^* = 24$					

Source: This research (2018)

Table 19 - Alternatives' ranking and their evaluations

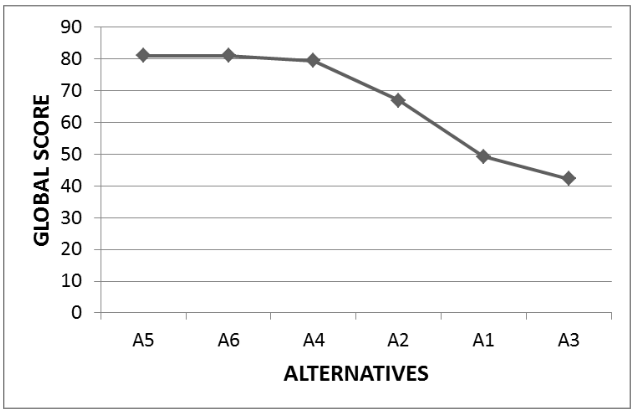
Ranking	Alternative	Global Score (GS_{Am})
1	A_5, A_6	81.071
2	A_4	79.405
3	A_2	66.963
4	A_1	49.208
5	A_3	42.280

Source: This research (2018)

Therefore, Figure 15 shows the global scores of the alternatives and gives us the magnitude of how preferable each alternative is in relation to the other. Note that the final result allows ties between alternatives stated by all individuals when comparing A5 and A6. So, the model does not oblige decision makers to express a forced opinion about a complete order of the alternative if it does not occur to them.

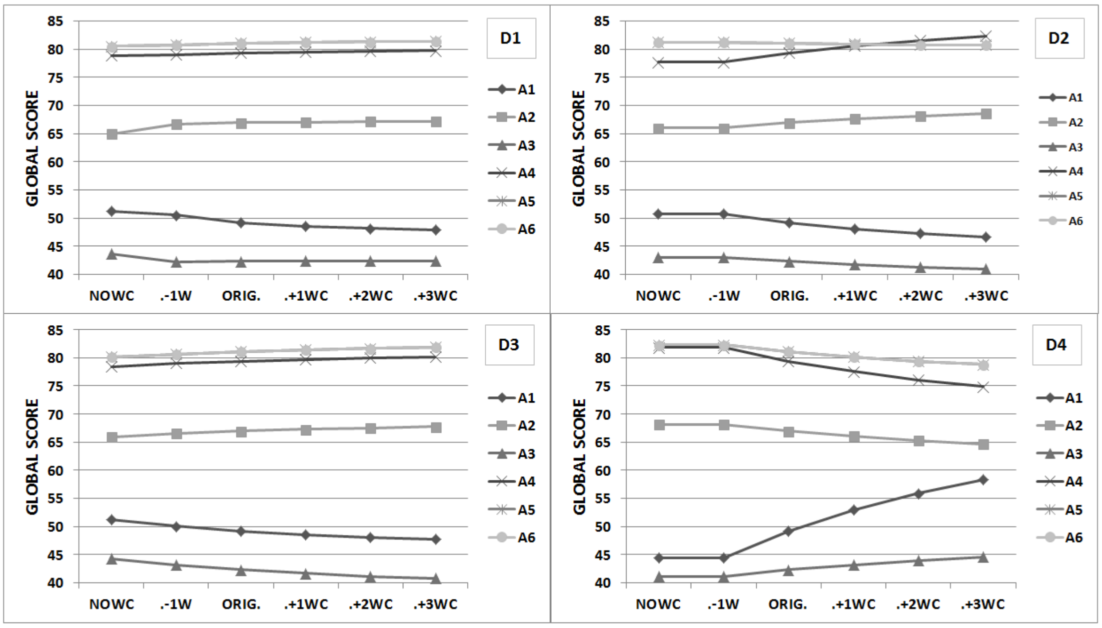
To better analyze the proposed methodology in this simulation, sensibility analysis was performed by varying the number of inserted white cards by the individuals and the removal of alternatives from set *A*. It may represent, respectively, some uncertainty of the individuals in expressing their opinions regarding the degree of preference between two or more alternatives and some modification that entails changing the set of alternatives, but without degeneration. Figure 16 represents the sensibility analysis performed individually for each member of the group by removing all white cards (NOWC) from the white cards levels, removing just one white card from each level (-1WC), inclusion of one white card (+1WC), inclusion of two white cards (+2WC), and the inclusion of three white cards (+3WC).

Figure 15: Ranking and preference intensity of the alternatives



Source: This research (2018)

Figure 16 - *Sensibility analysis*

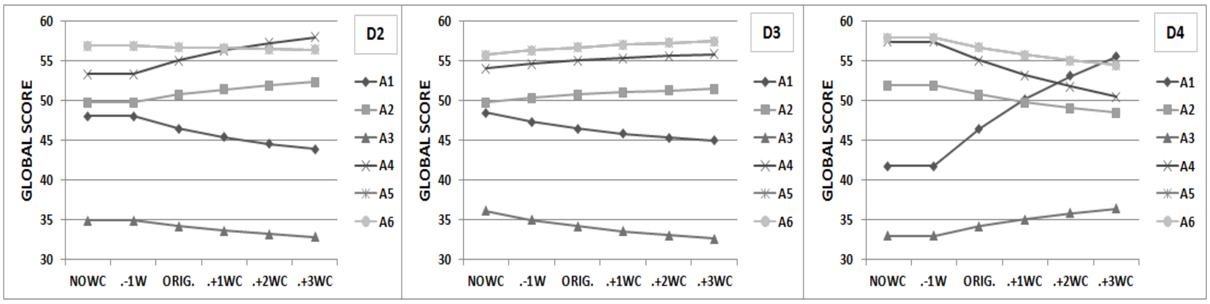


Source: This research (2018)

Note that the increase in the difference between the most desired and least desired alternatives is reflected in the overall score, and just the opposite occurs for D_4, which holds the most diverse point of view. The global score of A_4 is quite close to the winning alternatives and changing D_2 opinion by including two or more white cards causes a reversion in their order.

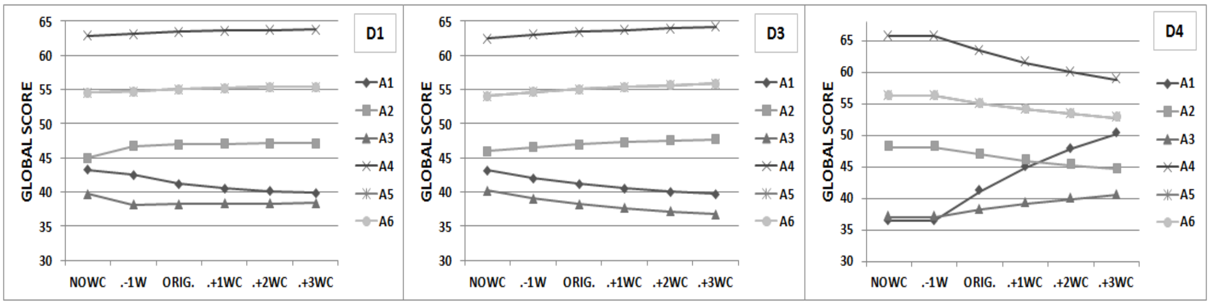
This group is quite cohesive, given that for three of the four individuals, A_5 and A_6 are top-ranked while A_1 and A_3 alternate between the last. To evaluate the sensibility in a less cohesive group, the individual D_1, D_2 and D_3 were removed one at a time from the analysis. Figures 17 to 19 show the behavior of the final rankings by the inclusion or exclusion of white cards.

Figure 17 - *Sensibility analysis without D1*



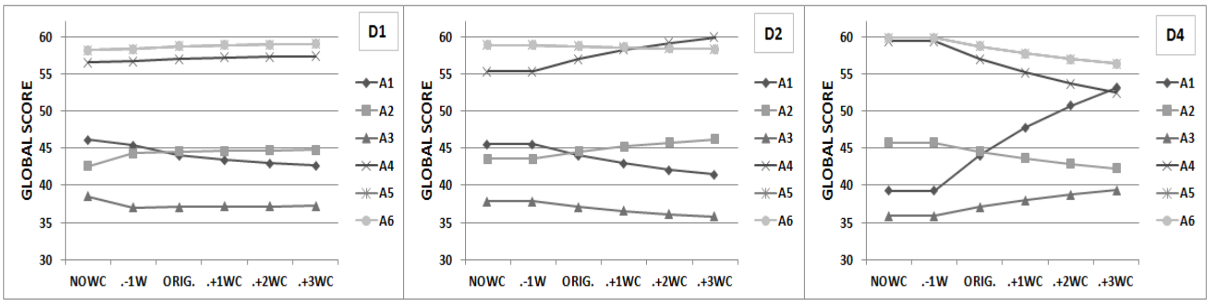
Source: This research (2018)

Figure 18 - *Sensibility analysis without D2*



Source: This research (2018)

Figure 19 - *Sensibility analysis without D3*



Source: This research (2018)

Note in Figures 17, 18 and 19 that the influence of changing minds in the final ranking is quite considerable. It is possible to see a reversal in many situations: when removing the preference profile of D_1 (Figure 5.5), A_4, A_5 and A_6 changes their positions in final rankings by changing D_2's cards and A_1 can move from fifth to first place when D_4 increases the number of white cards; without D_2, A_1 could reach the fourth position if D_4 increased its distance to the other alternatives; in the case without D_3 (Figure 5.7), A_1 and A_2 shift by reducing the number of white cards for any individuals, on the other hand A_1 can rise up two positions, and A_4 may be the best rated alternative if D_2 includes more white cards. This analysis shows the importance of considering the intensity of preference, since different results for the final ranking can be obtained in a way that represents in fact the yearnings of the group. However, it also demonstrates that the result of the proposed method is subject to strategic or dishonest voting since a certain individual can establish a vote that differs from his/her real preferences in order to prejudice alternatives that are not of his/her interest. In cases where this situation is detected by individuals or by a facilitator, it is recommended the use of a multi-criteria decision aid model in order to quantify individual preferences over alternatives.

Regarding the exclusion of the alternatives, some conditions were necessary to maintain the preferences intensities of the decision makers for the remaining alternatives: 1) if the excluded alternative belongs to a level occupied by other alternatives, its exclusion does not cause changes in the levels; 2) if the excluded alternative by itself composes an intermediate level, a white card is inserted in its level; and, 3) if the excluded alternative by itself composes an extreme level (best or worst), its exclusion entails the exclusion of its level and the adjacent white cards. As result, except for the exclusion of A_1, as shown in Table 20, the removal of alternatives one by one did not cause changes in the ranking among the remaining alternatives.

Table 20 - Alternatives ranking by excluding A_1

Ranking	Alternative	Global Score (GS_{Am})
1	A_4	93.227
2	A_5, A_6	91.597
3	A_2	73.537
4	A_3	50.042

Source: This research (2018)

It is possible to compare the result of the simulation with the application of the data from Tables 1 – 4 in other voting procedures. Table 21 presents the final rankings obtained by applying the methods of Borda (YOUNG, 1974), Condorcet (1785), Copeland (RICHELSON, 1978), Silva and Morais' (2014) linguistic-based, and Borda majority count (Zahid and Swart 2015). Some adaptations were necessary: as Borda, Condorcet, and Copeland do not consider preference intensity, the white cards were discarded; as Borda count requires a complete order of alternatives, it is considered two different rankings as input to deal with the ties: organizing the tied alternatives in alpha-numerical order (Borda-A) and its inverse order (Borda-B); for the Silva and Morais' (2014) method, the linguistic scale was built based on the disposition of the cards and its distance, normalizing the scores to a 0-100 scale and classifying this evaluation in a five level linguistic scale (low, between low and medium, medium, between medium and high, and high). The score for each level was the same as the Silva and Morais (2014) example. For the Borda majority count, the same converting process was applied, however considering a linguistic scale of six levels (rejected, poor, acceptable, good, very good and excellent), with correspondent scores of (0, 1, 2, 3, 4, and 5).

Table 21 - Comparing rankings by application of different methods

Ranking	Borda-A	Borda-B	Condorcet	Copeland	Silva and Morais	Borda maj. counting
1º	A4	A6	-	A4, A5, A6	A5, A6	A5, A6
2º	A5	A5		A2	A4	A4
3º	A2	A4		A1	A2	A2
4º	A6	A2	A2	A3	A1	A1
5º	A1	A1, A3	A1		A3	A3
6º	A3		A3			

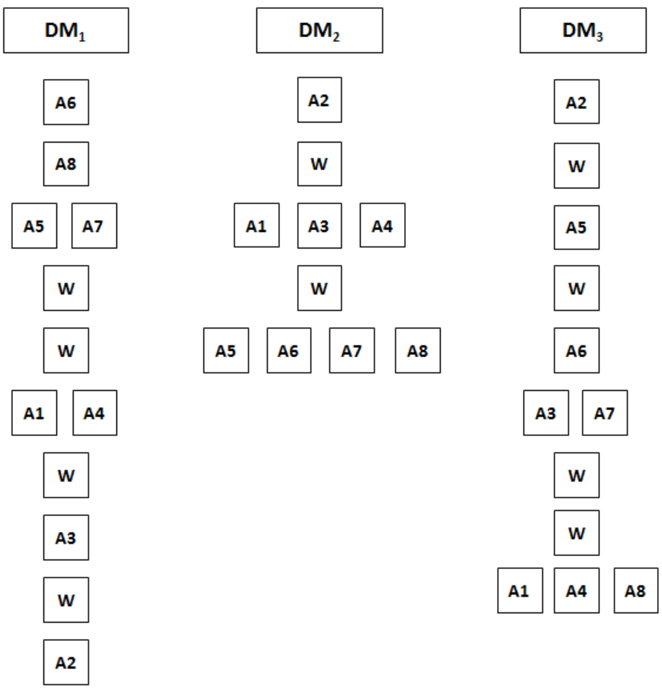
Source: This research (2018)

In Table 21, there is a perceptible difference between the rankings, mainly those generated by the application of the Borda count, which shows that forcing individuals to provide a complete ranking of alternatives when it does not actually exist in their minds can lead to a rather distorted result. Analyzing the result from the pairwise comparison methods, the Condorcet method cannot suggest a winner in this case because there is no transitivity relation between A4, A5, and A6, and Copeland presents these alternatives as a tie in the first position. The methods that consider linguistic scale to represent preference intensity obtained the same result and are equal to the ranking suggested by the proposed method (see Table 5).

5.2.2 Simulation 2

Simulation 2 was performed with a set of eight alternatives $A = \{A_1, A_2, A_3, A_4, A_5, A_6, A_7, A_8\}$ and a group of three individuals, $G = \{DM_1, DM_2, DM_3, DM_4\}$. Thus the 'playing cards' of each individual was considered the same as those performed by decision-makers in Fontana et al. (2011), who judged criteria for water conservations strategies. Figure 20 is the evaluation of the selected individuals in which the symbol '*W*' in a card represents that it is a white card.

Figure 20 - Individuals' preference represented by cards for simulation 2



Source: This research (2018)

Similarly to simulation 1, Tables 22 – 24 were built to compute the scores (S_i) attributed to each alternative by the individuals, calculating through Eq. 3, alternatives' global scores were obtained by Eq. 4. Table 25 presents the alternatives ranking after aggregation of individual scores, which is also showed in the graph of Figure 21, presenting that the alternatives A_1 and A_4 are the best compromise between individuals' preferences.

Table 22 - Obtaining scores for DM$_1$

Level	**Cards**	**N_i**	**r-value**	**S_i'**	**S_i**		**Alternatives' scores**	
1	A_6	1	1	1	2,123		A_1	15,957
2	A_8	1	2	2	4,255		A_2	25,532
3	A_5, A_7	2	3, 4	3,5	7,447		A_3	21,277
4	White	2	5	-	-		A_4	15,957
	White		6				A_5	7,447
5	A_1, A_4	2	7, 8	7,5	15,957		A_6	2,123
6	White	1	9	-	-		A_7	7,447
7	A_3	1	10	10	21,277		A_8	4,255
8	White	1	11	-	-			
9	A_2	1	12	12	25,532			
			$\sum r_i^* = 47$					

Source: This research (2018)

Table 23 - Obtaining scores for DM_2

Level	**Cards**	**N_i**	**r-value**	**S_i'**	**S_i**		**Alternatives' scores**	
1	A_2	1	1	1	2,128		A_1	8,511
2	White	1	2	-	-		A_2	2,128
3	A_1, A_3, A_4	3	3, 4, 5	4	8,511		A_3	8,511
4	White	1	6	-	-		A_4	8,511
5	A_5, A_6, A_7, A_8	4	7, 8, 9, 10	8,5	18,085		A_5	18,085
			$\sum r_i^* = 47$				A_6	18,085
							A_7	18,085
							A_8	18,085

Source: This research (2018)

Table 24 - Obtaining scores for DM_3

Level	**Cards**	**N_i**	**r-value**	**S_i'**	**S_i**		**Alternatives' scores**	
1	A_2	1	1	1	1,818		A_1	20,000
2	White	1	2	-	-		A_2	1,818
3	A_5	1	3	3	5,454		A_3	11,818
4	White	1	4	-	-		A_4	20,000
5	A_6	1	5	5	9,091		A_5	5,454
6	A_3, A_7	2	6, 7	6,5	11,818		A_6	9,091
7	White	2	8	-	-		A_7	11,818
	White		9				A_8	20,000
8	A_1, A_4, A_8	3	10, 11, 12	11	20,000			
			$\sum r_i^* = 55$					

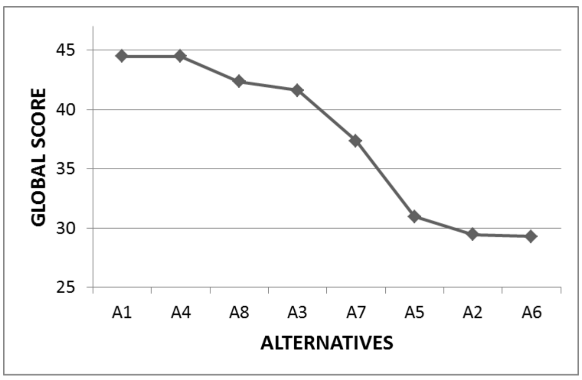
Source: This research (2018)

Table 25 - Alternatives' ranking and their evaluations for simulation 2

Ranking	**Alternative**	**Global Score (GS_{Am})**
1	A_1, A_4	44,468
2	A_8	42,340
3	A_3	41,605
4	A_7	37,350
5	A_5	30,986
6	A_2	29,478
7	A_6	29,304

Source: This research (2018)

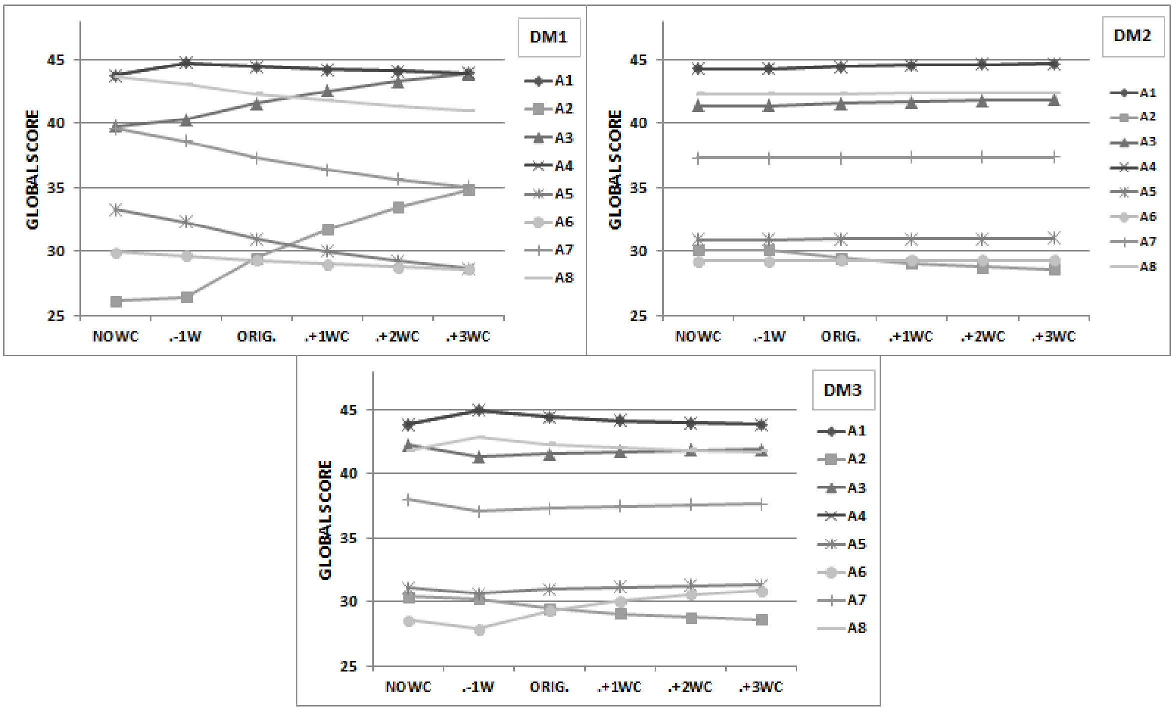
Figure 21 - Ranking and preference intensity of the alternatives for simulation 2



Source: This research (2018)

For simulation 2, sensibility analysis was performed considering the same variations of the sensibility analysis of simulation 1. Thus, the final ranking was analyzed by varying the number of white cards between the alternatives from zero to more three white cards. Figure 22 represents the consequences of these changing minds of each decision-maker in the final ranking of alternatives.

Figure 22 - Sensibility analysis of simulation 2



Source: This research (2018)

It is observed that changes in the intensity of preferences between alternatives have different degrees of impact in the final ranking for each decision maker. The ranking is less sensitive to changes in DM_2 preferences as there is only inversion in the position of the last ones placed A_2 and A_6 when increasing the number of white cards. This same inversion occurred when white cards are removed from DM_3, but this also entails the inversion of A_8 and A_3. However, the increase in the distance between the alternatives for DM_1 has great effect, since alternative A_2 move from the last position to the fifth and A_3 moving from third to the second one almost tied with the best placed. Thus, it is reinforced the importance of considering intensity of preference nevertheless one must take care to avoid strategic votes.

Regarding the removal of the alternatives, it was performed considering the same rules of simulation 1, aiming to maintain the same degree of preferences between the remaining ones. Although there are some inversions of positions in the ranking, the result was very consistent as can be observed by Table 26. So, although we cannot say that the method has independence of irrelevant alternatives, the result of applying this method is reliable even if there are small modifications in the set of alternatives according to the simulations performed in this work.

Table 26 - Final ranking by removing alternatives

Ranking	**Removed alternative**							
	A_1	**A_2**	**A_3**	**A_4**	**A_5**	**A_6**	**A_7**	**A_8**
1	A_4	A_1, A_4	A_1, A_4	A_1	A_1, A_4	A_1, A_4	A_1, A_4	A_1, A_4
2	A_8	A_8	A_8	A_8	A_8	A_3	A_8	A_3
3	A_3	A_3	A_7	A_3	A_3	A_8	A_3	A_7
4	A_7	A_7	A_2	A_7	A_7	A_7	A_5	A_5
5	A_5	A_5	A_5	A_5	A_6	A_5	A_6	A_6
6	A_2	A_6	A_6	A_2	A_2	A_2	A_2	A_2
7	A_6			A_6				

Source: This research (2018)

In order to compare the result of this simulation with those of applying this input in other methods, it is applied the same rule of simulation 1, since in simulation 2 the individuals also consider indifferences between alternatives. Thus, for the methods which require a complete ranking of alternatives, it is considered two different rankings: the first one, addressed in Table 27, puts the tied alternatives in alpha-numerical order, while the second one, addressed in Table 28, puts the tied alternatives in reverse alpha-numerical order. For the methods which considers a linguistic scale the scores obtained by playing cards were normalized into a 0-100 scale and the alternatives were classified and punctuated according linguistic scales presented in Silva and Morais (2014) and Zahid and Swart (2015).

For such cases, we can also conclude that forcing individuals to establish a complete ranking and not consider the alternatives' preference intensity can lead to a distorted result. However, differently from simulation 1, the most contrasting results were encountered when comparing the methods which consider preference intensity, that is: our proposal, Silva and Morais' (2014) procedure and the Borda Majority Counting (ZAHID; SWART, 2015). In this specific case is quite difficult to say which method presents the best performance, but it is advocated the procedure proposed in this thesis as the simpler voting procedure (among those which consider intensity of preference) and in this simulation presented the lowest number of draws between alternatives.

Table 27 - Comparison with results of other voting procedures 1

Ranking	Proposed method	Borda	Condorcet	Copeland	Quartile-based*	Silva and Morais	Borda maj. counting
1	A_1, A_4	A_1	A_1	A_1	A_1	A_8	A_1, A_4, A_8
2	A_8	A_3	A_3, A_4, A_5, A_7, A_8	A_4, A_3	A_3, A_5	A_1, A_3, A_4	A_3, A_7
3	A_3	A_4, A_5		A_5	A_6	A_7	A_5, A_6
4	A_7	A_7, A_8		A_7, A_8	A_2	A_6	A_2
5	A_5	A_6		A_6		A_5	
6	A_2	A_2		A_2		A_2	
7	A_6		A_6				
8			A_2				

**A_7 and A_8 are not placed in none of individuals first quartiles.*

Source: This research (2018)

Table 28 - Comparison with results of other voting procedures 2

Ranking	Proposed method	Borda	Condorcet	Copeland	Quartile-based*	Silva and Morais	Borda maj. counting
1	A_1, A_4	A_8	A_8	A_8	A_8	A_8	A_1, A_4, A_8
2	A_8	A_4	A_4	A_4	A_3, A_4, A_7	A_1, A_3, A_4	A_3, A_7
3	A_3	A_7	A_1, A_3, A_7	A_1, A_3, A_7	A_2	A_7	A_5, A_6
4	A_7	A_3		A_6		A_6	A_2
5	A_5	A_1		A_5		A_5	
6	A_2	A_2, A_5, A_6	A_6	A_2		A_2	
7	A_6		A_5				
8			A_2				

**A_1, A_5 and A_6 are not placed in none of individuals first quartiles.*

Source: This research (2018)

5.3 Model properties and analysis

Considering the criteria usually used to evaluate voting procedures (NURMI, 1983; PALHA et al., 2017), it is possible to create some propositions regarding the proposed method properties.

Property 1: The proposed method is a Condorcet-loser.

Proof: it is demonstrated through an example developed for this purpose. Table 29 represents the preferences of five decision-makers over a set of five alternatives, ordered from worst to best. In this case, A5 is a Condorcet-loser alternative and it is the best rated by the proposed procedure.

Table 29 - Condorcet-loser example

D_1	**D_2**	**D_3**	**D_4**	**D_5**
A_3	A_3	A_1	A_1	A_2
5 white	5 white	2 white	2 white	7 white
A_4	A_4	$\boldsymbol{A_5}$	$\boldsymbol{A_5}$	$\boldsymbol{A_5}$
10 white	10 white	A_2	A_2	A_1
$\boldsymbol{A_5}$	$\boldsymbol{A_5}$	A_4	A_4	A_3
A_2	A_1	3 white	3 white	3 white
A_1	A_2	A_3	A_3	A_4

Source: This research (2018)

Property 2: The proposed method is not a Condorcet-winner.

Proof: If all individuals rank the alternatives without the occurrence of ties and also do not use white cards, the result coincides with Borda counting, which is not a Condorcet-winner method (NURMI, 1983). Property 2 can also be extended to other procedures, as in Theorem 1.

Theorem 1: A social choice scoring function that considers intensity of preferences and aggregates them additively in a single stage can never be a Condorcet-winner method.

Proof: Consider an alternative set A = {$A_1, ..., A_x, A_y, ..., A_m$} and a group with n individuals. For A_x to be a Condorcet-winner alternative, it must be better than all the other alternatives for the majority of the group, that is for at least ($n/2+1$) individuals. Suppose A_x is a Condorcet-winner. Considering P^i the preference intensity (difference in preference) of A_x over A_y for the majority who prefers A_x to the detriment of A_y. Considering P^j the preference intensity (difference in preference) of A_y over A_x for the minority who prefers A_y to the detriment of A_x. If individuals are free to state their preferences, there are no restriction on the values assigned to P^i or P^j. Since there is no restriction to P^i or P^j and the model is additive, it is possible that P^j is greater than P^i, although it is the opinion of the smallest part of the group. This compensation makes possible the victory of Ay as its global performance may be greater than global performance of A_x leading to not choosing the Condorcet-winner.

Property 3: The proposed procedure is monotonic.

Proof: Considering A_x is the winner by applying the proposed procedure. In order to keep the preferences over the remaining alternatives, it is not possible to change the arrangement of white cards, so the only way to put A_x in a higher position is to shift A_x by any other alternative at a higher level. It directly implies the reduction of the global score of this alternative and an increase of the global score of A_x, which is already the winner.

Property 4: The proposed procedure respects the Pareto-optimality condition.
Proof: Directly from the way the individual evaluations are performed, if A_x is preferred to Ay, then $S^i_{A_x} > S^i_{A_y}$. Since the global score (GS_{A_x}) is obtained by $\sum_{i=1}^{n} S^i_{A_x}$, consequently $GS_{A_x} > GS_{A_y}$.

Property 5: The proposed method is dependent of irrelevant alternatives.
Proof: The sensibility analysis for D_2 in Section 5.5 shows that the social choice over {A4, A5, A6} changes by increasing the difference of preference intensity between A1 and A4. See the Figure 4 for D_2. Alternatively, the result of alternatives removal simulation can be considered for its demonstration. When the method is applied with $A = \{A_1, A_2, A_3, A_4, A_5, A_6\}$ the choice is $\{A_5, A_6\}$. However, when applied with the subset $A' = \{A_2, A_3, A_4, A_5, A_6\}$, the choice is $\{A_4\}$. See Table 6.

Property 6: The proposed procedure does not satisfy the Chernoff condition.
Proof: The same as property 5.

Chernoff condition is a prerequisite to a procedure to obey the path independence property (SUZUMURA, 2016). In relation to non-compliance with the criteria from definitions 4, 5, and 6, this should not be considered a serious problem given the Arrow's impossibility theorem and the fact that most voting methods do not obey it (PALHA et al. 2017).

The model is more susceptible to this order reversal when an alternative is evaluated as the best, or the worst alternative is not considered in a certain subset of *A*. It occurs because in such cases there is a huge modification in the ratio *Z*, consequently altering the extent of the preference unit u, resulting in scores substantially different.

Property 7: The proposed procedure is invulnerable to no-show paradox.
Proof: Supposing that all individual express their choices according to their preferences, as the model aggregates additively the individuals' opinions in just one round and the score

attributed to an undesired alternative is never higher than that attributed to the desired one, their abstention reduces the score that could be attributed to the desired alternative.

Property 8: The proposed procedure is consistent.

Proof: If A_x is the winner for *G'*, then $GS'_{A_x} = \sum S_{A_x}$ is the greatest global score value in the alternatives from the set *A*, evaluated by *G'*. The same is valid for *G''*. Directly from Eq. 4, $GS_{A_x} = \sum GS'_{A_x} + GS''_{A_x}$for the group *G = (G' ∪ G'')*. As GS'_{A_x} and GS''_{A_x} are respectively the greatest for *G'* and *G''*, GS_{A_x} is the greatest for *(G' ∪ G'')*, so A_x is also the winner.

Finally, regarding the criteria related to the complexity of applying the voting procedure for both the voters and the facilitator, who will process the individuals' information and convert them into a result, the procedure presents

Property 9: The proposed procedure does not present the easiness property, since it is not implemented with dichotomous information from individuals.

Property 10: The proposed procedure is endowed with simplicity, as it is performed requiring just one round of preference elicitation from individuals.

The main advantage of the proposed method is the consideration of the intensity of preference between the alternatives. Traditional voting procedures are based only in a full ranking or in a choice of a single alternative. That is, they are methods based on partial information and do not always represent the wishes of the decision makers. Any multi-criteria method whose result is a complete preorder can be applied to obtain the individual rankings or even the intensity of preference. However, it should be noted that the model does not admit the incomparability relation; otherwise, the condition of exhaustiveness would not be satisfied.

The effort level to elicit individuals' preferences is similar to linguistic scale models and less than models that require pairwise comparison. Sometimes, individuals feel uncomfortable performing an evaluation using a nominal scale. In such models, the linguistic scale must be the same for all individuals and the scale levels are not necessarily sufficient to represent the nuances between alternatives present in their minds. In other words, each one can have their own scale to judge the alternatives representing them cardinally by playing cards and the normalization process adjusts the scores to the same order of magnitude. Note that the proposed method of this chapter eliminates the previous step of creating a linguistic scale.

Moreover, it is easy to apply and may be implemented in any decision environment involving a group of individuals to treat a problematic of ranking alternatives. The model also deals with choice problems by just selecting the best rated alternative. The method is classified as a ‘one-stage procedure’ (NURMI, 1983) since it requires only one round of preference elicitation with individuals.

Comparing with the properties of other methods, it can be highlighted that when considering traditional voting methods (based on single choice or full ranking form individuals), the proposed methods enriches the voting by considering intensity of preferences. In contrast, the proposed method does not meet Condorcet criteria. When considering linguistic scale based methods, they are in most independent of irrelevant alternatives. However, they are not always simple since may involve a step for creating the linguistic, moreover this scale may not be enough to represent DMs preferences.

5.4 Illustrating the proposed model in a water management context

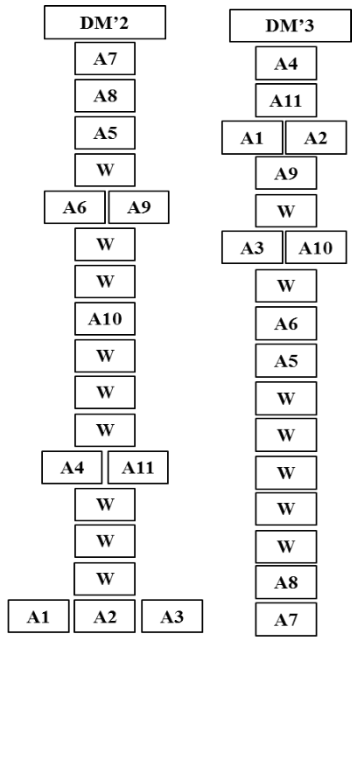
This section provides an analysis of a possible scenario for a group decision-making in the case of seeking improvements for Olinda’s water supply system, as presented in Chapter 3. For this, it is necessary to consider preferences profiles for decision-makers, which were simulated as described below.

The first decision-maker (DM’1) in this simulation has his alternatives ranking obtained from FITradeoff elicitation performed in Chapter 3. Even though this methodology just solves choice problems, when eliciting and solving the problem FITradeoff software provides a set of weights which maximizes the performance of the best alternative: 0.75 for water loss index, 0.25 for the cost of alternative and 0.25 for water availability for consumers, which can also be visualized in Figure 3.7. This set of weights can be applied to whole set of alternatives considering the consequences matrix, providing a ranking of them. The preferences intensities for DM’1 were supposed as if he wanted a higher evaluation of his top ranked alternatives and punish the lowest ones in his ranking. Figure 5.11 represent the cards allocation.

Aiming to simulate a second decision-maker (DM’2), alternatives are ordered from its contribution to increase the water availability for consumers. Note that this is the same criterion applied to describe consumers’ preferences when considering their opinion for maintenance planning, as in chapter 4. For DM’2, it is considered a preference profile where little increase in availability levels from the current situation generates a considerable increase in preference intensity. However, when certain availability level is achieved, a gain in availability does not represent the same gain in preferences. In other words, the preference intensity measured by the number of white cards between two alternatives is bigger in the basis and reduces as it goes towards the top ranking alternatives, as showed in Figure 21. Alternatives allocated at the same level have the same performance on availability criterion according to the consequences matrix (Table 5).

Considering a third decision-maker (DM'3) with a cost-oriented point of view of this problem, the cost of alternatives is applied to provide a ranking of alternatives. So, an alternative is worse the higher its cost, but DM'3 also considers a budget for the improvement of Olinda's water supply system, which should not exceed $50 million. He presents a high level of rejection to alternatives that bring a cost higher than this value, separating this category by including 5 white cards, as in Figure 23. Tied alternatives present the same cost for their implementation, according consequence matrix (Table 5). Thus the simulated judgment of these decision-makers represented by playing cards is as follow:

Figure 23 - Playing cards scheme for model illustration



Source: This research (2018)

Tables 30 to 32 presents the obtaining scores for each simulated decision-makers' preferences, which are aggregated in Table 33 and plotted in Figure 24.

Table 30 - Obtaining scores for DM'1

Level	Cards	Ni	r-value	Si'	Si		Alternatives' scores	
1	A8	1	1	1	1,075		A1	6,451
2	A3	1	2	2	2,150		A2	5,376
3	A9	1	3	3	3,225		A3	2,150
4	A4	1	4	4	4,301		A4	4,301
5	A2	1	5	5	5,376		A5	17,204
6	A1	1	6	6	6,451		A6	16,129
7	White	3	7				A7	21,505
	White		8				A8	1,075
	White		9				A9	3,225
8	A11	1	10	10	10,752		A10	11,827
9	A10	1	11	11	11,827		A11	10,752
10	White	3	12					
	White		13					
	White		14					
11	A6	1	15	15	16,129			
12	A5	1	16	16	17,204			
13	White	3	17					
	White		18					
	White		19					
14	A7	1	20	20	21,505			
			$\sum r_i^*$ =93					

Source: This research (2018)

Table 31 - Obtaining scores for DM'2

Level	Cards	Ni	r-value	Si'	Si		Alternatives' scores	
1	A1, A2, A3	3	1, 2, 3	2	1,653		A1	6,451
2	White	3	4				A1	1,653
	White		5				A2	1,653
	White		6				A3	1,653
3	A4, A11	2	7, 8	7,5	6,198		A4	6,198
4	White	3	9				A5	14,876
	White		10				A6	12,810
	White		11				A7	16,529
5	A10	1	12	12	9,917		A8	15,702
6	White	2	13				A9	12,810
	White		14				A10	9,917
7	A6, A9	2	15, 16	15,5	12,810		A11	6,198
8	White	1	17					
9	A5	1	18	18	14,876			
10	A8	1	19	19	15,702			
11	A7	1	20	20	16,529			
			$\sum r_i^*$ =121					

Source: This research (2018)

Table 32: Obtaining scores for DM'3

Level	Cards	Ni	r-value	Si'	Si		Alternatives' scores	
1	A7	1	1	1	0,930		A1	14,419
	A8	2	2	2	1,860		A2	14,419
	White White White White White	3 4 5 6 7	3 4 5 6 7				A3 A4 A5 A6 A7	10,698 16,744 7,442 8,372 0,930
	A5	8	8	8	7,442		A8	1,860
	A6	9	9	9	8,372		A9	13,023
	White	10	10				A10	10,698
	A3, A10	11, 12	11, 12	11,5	10,698		A11	15,814
	White	13	13					
	A9	14	14	14	13,023			
	A1, A2	15, 16	15, 16	15,5	14,419			
	A11	17	17	17	15,814			
	A4	18	18	18	16,744			
			$\sum r_i^* =107,5$					

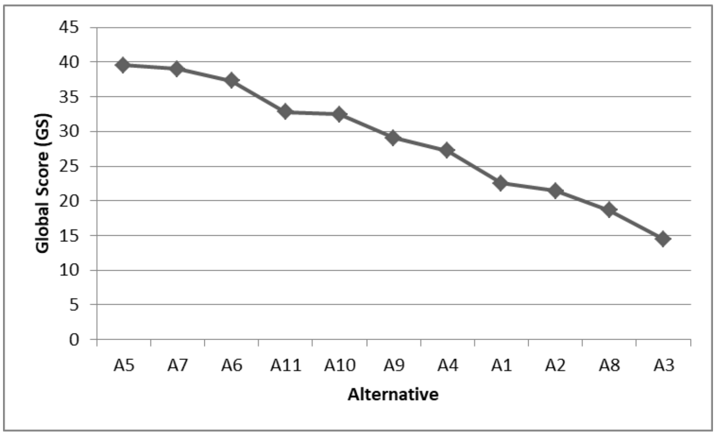
Source: This research (2018)

Table 33 **-** *Global scores for Olinda's case simulation*

Ranking	Alternative	Global Score (GS_{Am})
1	A5	39,52219
2	A7	38,96453
3	A6	37,31104
4	A11	32,76499
5	A10	32,44299
6	A9	29,05898
7	A4	27,24361
8	A1	22,52311
9	A2	21,44784
10	A8	18,63821
11	A3	14,5011

Source: This research (2018)

Figure 24 **-** *Alternatives ranking and preferences intensities*



Source: This research (2018)

In this case, the chosen alternative is A5, which is the increase the number of water network sectors (Section 3.3.3). Note that this alternative is different from that recommended when applying VFT and FITradeoff with one decision-maker (Chapter 3), although it is the second ranked. A7 was not chosen even though it is the top ranked alternative for two out of three individuals, probably due to the high rejection from DM'3. This simulation brings again the necessity of consider structuring the problem and eliciting preferences with other decision-makers involved in this context. Thus, the case analysis can be more comprehensive, and may propose another alternative if it is the one which best represents the compromise between the different preferences of individuals involved.

5.5 Chapter remarks

Following the proposal to consider intensity of preferences of decision makers over alternatives in voting models, this paper presents a model in which the individuals should express the desirability difference between the alternatives by the Simos' playing cards Procedure. The scores are aggregated in an additive way so that the global score represents the individuals' real desire about the adoption of a given alternative. The model is a good option when decision-makers want to include this information in aggregation process, but do not have the methodological support of a multicriteria decision-making model for groups.

The model is analyzed according to well-established criteria for the judgment of voting methods through axiomatic demonstrations. The drawback of the proposed procedure is that it may be possible to favor some form of a dishonest vote and present a dependence of irrelevant alternatives, although with low sensitivity from simulation. Regarding the latter, most methods have the same disadvantage. The method does not necessarily choose a Condorcet winner; however, no method that aggregates the preferences additively and considers intensity of preference obeys this property.

It is possible that one or more decision-makers face difficulties in establishing their preferences as required as input to the proposed method. In situations like this, multiple criteria decision-making methods (MCDM) can be applied for the elicitation of the complete preorder of the alternatives as well as for assisting in the cards' disposition. In addition, these methods can also be applied to favor the honesty of individual elicitations, ensuring an even more trustworthy result for the group.

The proposed procedure follows the criterion of individual rationality by monotonicity as well as the collective rationality criterion by Pareto-optimality. The procedure is consistent. In other words, it is invariant to consider different subgroups of individuals or all at once.

Moreover, no individual can benefit from abstaining from voting. The model does not require much effort from individuals when compared with other methods which includes such cardinalities between alternatives, favoring the use of this new social choice function.

6 CONCLUSIONS

Water distribution in urban areas can become inefficient for several reasons, which are illustrated in two case studies. Regardless of the cause of these malfunctions, the water supply company should make assertive decisions so as to achieve good system performance. It is not a simple decision environment: alternatives may have high costs; it is a service provided to a large number of consumers; it involves a considerable number of criteria; and it may involve more than one decision maker — the decision makers involved might not necessarily be concordant with one another.

In this context, this research developed models for supporting individuals and groups of individuals in order to reach the solution with the best compromise between their objectives and conflicting opinions. The first model supports an individual in problem structuring and in the choice of an alternative; the second model also deals with choice problems, but involves more than one decision maker; the third model solves problems of ranking alternatives for groups of decision makers with the feature of considering the intensity of preferences over alternatives. The models for groups are based on social choice theory, which the analysis of their properties are also based on. Conclusions in relation to the models and case studies are detailed below.

Chapter 3 examined the Olinda water supply case, describing the problem and supporting the decision maker in finding the best alternatives for the context, providing guidelines for prioritizing activities. His objectives can be considered a guide for defining the action plans for the company, and are also useful in the elaboration of the company's strategic planning. This study also has an impact on the social sphere, since it involves access to a right that is constitutionally guaranteed in Brazil and exhibits the necessity for the manager to perform the judgment of values so as to guarantee the functioning of the water supply system. Regarding the model, VFT provides the means for the decision maker to identify his objectives and to search for new solutions in an efficient manner, while FITradeoff reduces the effort without reducing the quality of the results. Although based on partial information, each iteration reduces the space of potentially optimal alternatives until there is only one, which, in fact, corresponds to the alternative of higher performance according to the preferences of the decision maker and, consequently, is the one that best meets its objectives for the structured case.

Chapter 4 addressed the context of group decision making. The option to study social choice theory was made because it does not require information on the initial preferences of decision makers (objectives, criteria, consequence matrices, and so on), but only their judgments in respect of alternatives. A quartile-based voting model was applied in the management of pumps for water distribution, aiming to define the interval of preventative maintenance, which made it possible to reduce maintenance costs and increase water availability to consumers. Model properties have been described in terms of the social choice theory and Arrow's condition. Application and analysis of the model showed that, despite its positive features regarding obeying the essential criteria of voting procedures and the advantage of reducing the set of alternatives focusing on those most important, the model has as input a complete ranking of alternatives which may not be enough to describe the real preferences of the decision makers.

Aiming at remedying such deficiencies, a model which allows intensity preference as well as indifference between alternatives was developed in chapter 5. The basis of the model is that of playing cards counting created by Simos for defining criterion weights. The proposed voting method makes a contribution to the literature on social choice, since it is a new way of eliciting individual preferences for subsequent aggregation. This thesis presents the method and, through simulation and sensitivity analysis, shows the use of the method as well as the effect that causes the inclusion of the intensity of preferences in these situations. In addition to considering preference intensity, simplicity makes its application feasible in future problems. The proposal is that in the future this model be applied in the case of Olinda water distribution, aggregating the preferences of other individuals who play an important role in this decision environment.

In addition to defining the properties of this model, the thesis provides a theorem that defines the conditions under which a voting method cannot be considered a Condorcet winner, that is, they cannot always choose the alternative that overcomes the others in a peer-to-peer comparison. This finding is another contribution to the literature on social choice, which may guide the development of new models and the application in new cases of those models already developed, including what is presented in this text.

6.1 Contributions of this thesis

This thesis presents models for problem structuring, individual decision making and group decision making in order to support the management of water supply systems seeking their improvement. This enriches the literature on water resources management and operations research, and can contribute to the provision of a better water service.

Applying FITradeoff to establish criterion weights after applying VFT facilitated the decision process for the described case: the decision maker answered only eight questions in order to obtain a solution from 11 alternatives and six criteria. Merging these methodologies so as to compose a decision aid model for the case reduced the effort to reach the alternative with the best compromise for the criteria considered by the manager, and with great assertiveness, since the recommended alternative was created while aiming to meet his objectives. The solution gives insights for solving other urban water problems in the future, achieving the objectives of the operations manager, and also generates benefits for the local population, as the result increases the quality of water services provision.

Regarding group decision making, this thesis brings a model for the preventative maintenance management of pumps for water distribution. This application considers reliability engineering models for describing individuals' preferences. Alternatives rankings were obtained by different MCDM methods, considering the most appropriated for the reasoning of each individual, and also avoiding strategic voting. It provides a detailed analysis of the quartile-based voting procedure.

From this application and from the literature review, it is possible to note the necessity of a model that considers the preference intensity between alternatives, enriching the voting process with more information on decision makers' preferences in a simple way. Furthermore, the adaptation of Simos' procedure for alternatives evaluation had not yet been studied in a group decision-making context. Chapter 5 describes the developed model, evaluates it according to social choice theory, and presents a theorem regarding the impossibility of methods which considers preference intensity being a Condorcet winner method.

The research developed in this thesis culminated in papers that are listed below.

- DE ALMEIDA-FILHO, A. T., MONTE, M. B. S., MORAIS, D. C. A voting approach applied to preventive maintenance management of a water supply system. Group Decision and Negotiation, 26:523-546, 2017.
- MONTE, M. B. S., MORAIS, D. C. Decision Model for Identifying and Solving Problems in an Urban Water Supply System (draft).
- MONTE, M. B. S., MORAIS, D. C. Aggregating individuals' rankings incorporating intensity of preference of the alternatives (draft).

- MONTE, M. B. S., MORAIS, D.C., GOMES, S. F. A value-focused consumer's perspective with multiattribute evaluation of the water distribution system of a Brazilian city. In: IEEE International Conference on Systems, Man and Cybernetics 2017, October 5-8, Banff-AB, Canada. Proceedings of 2017 IEEE SMC, 3350-3355, 2017
- MONTE, M. B. S., MORAIS, D. C. Aplicação do VFT para a gestão de operações do abastecimento de água na região de preservação histórica de Olinda-PE. In: XLIX Simpósio Brasileiro de Pesquisa Operacional, 27-30 de Agosto de 2017, Blumenau-SC. Anais do XLIX Simpósio Brasileiro de Pesquisa Operacional, 194-205, 2017
- MONTE, M. B. S., MORAIS, D. C., DE ALMEIDA-FILHO A. T. Analysis of the decision-makers' weights on preventive maintenance in a water supply system. In: IEEE International Conference on Systems, Man and Cybernetics 2016, October 9-12, Budapest, Hungary. Proceedings of 2016 IEEE SMC, 1092-1097, 2016

6.2 Limitations

Regarding chapter 3, despite having presented the entire decision-making process, it considers only the vision of one decision maker. Although he is the manager of on-site operations, and has a broad view of the system, there may be other issues that could be considered in the study if other individuals were consulted. Among them, other employees of the Water Supply Company, water resources experts, and consumers could be considered. Furthermore, decisions are not always in respect of the problem of choice and the model for individual decision making proposed in this thesis is not yet capable of dealing with ranking or classification problems.

Regarding the voting models, the limitations are related to the criteria that the procedure does not satisfy. Therefore, since they do not present the independence characteristic of irrelevant alternatives, the model may not be suitable for the situations wherein the set of alternatives may change during the course of the decision process. They are also not recommended to apply when the set of alternatives has to be partitioned, as there is path dependence. There is also the limitation of the possibility of dishonest voting; despite being a problem, the use of multi-criteria decision aid models can reduce this drawback.

6.3 Future works

- To structure the problem with other stakeholders in order to have a broader view of local water distribution and possibly generate new alternatives.
- To incorporate the more recent FITradeoff models aiming to solve the problem of ranking alternatives.
- To apply the voting model in a real situation both in water management and in other contexts, since this can also generate proposals for model improvement.
- To propose an addendum to the model that reduces the number of alternatives, making its application feasible in cases with a large number of alternatives.

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