THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Decision Support Model for a Sustainable Regional Water Supply

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2018

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Chalmers reproservice
Göteborg, Sweden 2018

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ABSTRACT

Water supply provision has traditionally been a municipal responsibility. However, environmental, social and economic drivers are now making it more attractive to manage the water services in a more aggregated way. Yet, even though municipalities have cooperated to improve their water supply provision for decades, the topic is fairly under-researched and advantages and disadvantages not fully understood. Further, decisions regarding drinking water cooperation and other regional interventions are often made without a proper method of balancing, for example, the economic, health and environmental effects thereof. This thesis presents a decision support model to aid in regional water supply decision-making. The model is based on a combination of cost-benefit analysis and multi-criteria decision analysis for sustainability assessments of regional water supply interventions, including formations of inter-municipal cooperations. The proposed model integrates quantitative and semi-quantitative information on sustainability criteria, and it provides a novel way of presenting monetized benefits and costs with non-monetized social and environmental effects of regional water supply alternatives. The decision support model is based on a probabilistic approach where uncertainties are represented by statistical probability distributions and modeled by means of Monte Carlo simulations. A case study is used to exemplify and evaluate model application in decision situations regarding regionalization of water governance, (de)centralization of water production, and source water quality and redundancy aspects. The proposed model can be used by decision-makers to develop coherent preferences within economic, environmental and social sustainability so that decisions on regional water supply interventions can be taken with a higher degree of confidence. The results of the thesis contribute to a decision support toolbox needed to make proper evaluations and informed decisions in order to achieve long term sustainable water supply solutions.

Keywords: drinking water supply, decision support, regionalization, inter-municipal cooperation, sustainability, multi-criteria decision analysis, cost-benefit analysis, economic valuation

LIST OF PAPERS

This thesis includes the following papers, referred to by Roman numerals:

I. Sjöstrand, K., Lindhe, A., Söderqvist, T., and Rosén, L. (2018). Sustainability assessments of regional water supply interventions – combining cost-benefit and multi-criteria decision analyses. Submitted to *Journal of Environmental Management*.

II. Sjöstrand, K., Lindhe, A., Söderqvist, T., and Rosén, L. (2018). Cost-benefit analysis for supporting inter-municipal decisions on drinking water supply. Submitted to *Journal of Water Resources Planning and Management*.

Division of work between authors

In paper I, Sjöstrand, Lindhe and Rosén defined the aim and objectives of the study, designed application scenarios and were part in developing the model. Sjöstrand designed the model and performed all calculations. Söderqvist contributed with expert knowledge regarding cost-benefit and multi-criteria decision analyses. Sjöstrand was the main author of the paper.

In paper II, all authors formulated the decision problem and defined the aim and objectives of the study. Sjöstrand structured the cost-benefit model, gathered and analyzed the input data, performed all simulations and was the main author of the paper.

Other work and publications not appended:

- Sjöstrand, K., Lindhe, A., Söderqvist, T., and Rosén, L. (2018). *Input data report for economic assessments of water supply interventions in the Göteborg region.* Chalmers University of Technology
- Sjöstrand, K. (2017). *A Literature Review on Regional Water Governance, Multi-Criteria Decision Analysis, Cost-Benefit Analysis and Sustainability Assessments.* Chalmers University of Technology
- Sjöstrand, K., Rosén, L., Kärrman, E., Blom, L., Ivarsson, M., Lång, L.-O-, Friberg, J., and Lindhe, A. (2017). *Holistic decision support model to ensure a sustainable regional water supply* (E-poster). Oral presentation at the Swedish Water and Wastewater Conference Research and Innovation for Safe Drinking Water (Forskning och Innovation för Säkert Dricksvatten), Stockholm, Nov 28-29.

- Sjöstrand, K., Rosén, L., Kärrman, E., Blom, L., Ivarsson, M., Lång, L-O., and Lindhe, A. (2017). *Water supply decision-making for a sound prioritization of society's limited resources* (Abstract). Poster presentation at the Fifth Annual International Conference on Sustainable Development (ICSD), New York City, Sept 19-20.
- Sjöstrand, K., Rosén, L., Kärrman, E., Blom, L., Ivarsson, M., Lång, L-O., and Lindhe, A. (2017). *Sustainability Assessment of Water Supply Plans Using Cost Benefit Analysis and Multi Criteria Analysis* (Abstract). Poster presentation at the 2017 Sustainable Water Management Conference, New Orleans, March 19-22.
- Sjöstrand, K., Rosén, L., Kärrman, E., Blom, L., Lindkvist, J., Ivarsson, M., Lång, L-O., and Lindhe, A. (2016). *Combining cost benefit analysis with multi criteria analysis for sustainability assessment of regional water supply policies* (Abstract). Poster presentation at the Society for Risk Analysis Annual Meeting, San Diego, Dec 11-15.
- Sjöstrand, K., Rosén, L., Kärrman, E., Blom, L., Lindkvist, J., Ivarsson, M., Lång, L-O., and Lindhe, A. (2016). *Decision support for assessing the socio-economic value of a regionalized water supply* (Abstract). Oral presentation at the 2016 AWRA Annual Water Resources Conference, Orlando, Nov 13-17.
- Sjöstrand, K., Rosén, L., Kärrman, E., Blom, L., Widerberg, A., Lindkvist, J., Lång, L-O., and Lindhe, A. (2016). *Decision-support for a sustainable regional water supply management* (Abstract). Oral presentation at the 10th Nordic Drinking Water Conference, Reykjavik, Sept 28-30.

ACKNOWLEDGEMENTS

This research was performed within the DRICKS center for drinking water research at Chalmers University of Technology. The research was funded by the Swedish Research Council Formas with support from the Göteborg Region Association of Local Authorities, the City of Göteborg, and RISE Research Institutes of Sweden. I thankfully acknowledge all financiers for their support.

I would like to express my sincere gratitude to my supervisors at Chalmers University of Technology, Professor Lars Rosén and Dr. Andreas Lindhe. Thank you for your invaluable support and encouragement. I appreciate your advice and our discussions a lot.

I would also like to thank Erik Kärrman at RISE Research Institutes of Sweden, Tore Söderqvist and Mats Ivarsson at Anthesis Enveco, Lena Blom at the City of Göteborg, Lars-Ove Lång at the Geological Survey of Sweden, Jacob Lindkvist and Joanna Friberg at the Göteborg Region Association of Local Authorities, and all stakeholder participants for contributing in model development and for valuable input in the application of the model in the Göteborg region.

The work on this thesis was carried out mainly in the United States and I am forever grateful to everyone who contributed in making that possible: to Charlotta Möller at RISE Research Institutes of Sweden for encouraging me to take the step; to Lars Rosén, Andreas Lindhe and Erik Kärrman for believing in, and having a tremendous patience with, this long distance doctoral collaboration; to Professor Upmanu Lall at Columbia University in the City of New York for welcoming me as a visiting research scholar at Columbia Water Center; and to my mother Gudrun Öberg and mother in law Birgitta Skoglund for your innumerable travels to the US to help out when I’ve been away. This American life adventure could not have happened without any of you. Thank you!

Finally, I would like to thank my Atlantic Highlands friends for all your love and distraction, and for keeping me at least partly sane during this process. And the warmest thanks to my family, Karl, Arvid and Olle, for your love, patience and encouragement, and for being my everyday motivation. Love you!

Atlantic Highlands, 2018

Karin Sjöstrand

TABLE OF CONTENTS

1 INTRODUCTION

This chapter gives a background to the thesis, outlines the aim and objectives, and presents the scope and limitations of the study.

1.1 Background

Drinking water constitutes a fundamental public good, which is crucial to all social development. Access to safe and reliable drinking water sets the framework for business development as well as public health and well-being. However, the water sector faces serious challenges, and the demands on our public drinking water providers are growing. The challenges include difficulties in meeting financial requirements for maintaining and improving both new and ageing infrastructure along with increasing requirements regarding emergency preparedness, climate change mitigation and efficiency in production and distribution (Palaniappan et al., 2007; Rygaard et al., 2014; SOU 2016:32).

In Sweden, as in many other countries, the responsibility of providing drinking water to society lies on the municipalities. But with an increasing need to handle the above mentioned challenges, the interest in managing water supply on a more aggregated level is growing. Hence, to gain common resource benefits, local water utilities in Sweden and other countries form regional, inter-municipal, cooperations (Kurki et al., 2016; Thomasson, 2018). However, decisions regarding drinking water cooperations and other regional interventions are often made without a proper method of balancing, for example, the economic, health and environmental effects thereof (McFarlane, 2003).

In the water sector, as in many other sectors, decisions have traditionally been highly influenced by economics. However, there is a growing international consensus that not only economic but also social and environmental effects need to be considered and addressed in water supply decision-making (Liner & deMonsabert, 2011). Furthermore, the rising importance of regional governance implies an increased need for a customized and professionalized decision-making process to solve the common challenges (Lieberherr, 2011; Schmidt, 2014). Water utility decision-makers are hence faced with decision situations not only concerning what to do to secure a safe and reliable drinking water supply, but also how to prioritize alternatives based on an evaluation of their sustainability, and how to ensure an inclusive and structured decision-making process on an inter-municipal level.

Decision support methods are commonly used to assist decision-makers in the complex task of evaluating and prioritizing between alternative solutions to a given problem. A water supply sustainability assessment method needs among other things to be transparent, valid and holistic (Brattebø et al., 2013). It also needs to allow for public and stakeholder participation, which has been recognized as essential for good public policy (UNECE, 1998), and it needs to consider uncertainties and trade-offs in future context conditions (Störmer et al., 2009). A number of studies have focused on evaluating the sustainability of local water supply interventions using different evaluation methods such as multi-criteria decision analysis (MCDA) (Godskesen et al., 2017; Rygaard et al., 2014), cost-benefit analysis (CBA) (Mukheibir & Mitchell, 2011), life cycle assessments (Lundin & Morrison, 2002) and optimization techniques (Lim et al., 2010). There are, however, few decision support tools adapted to the inter-municipal level, allowing for a structured handling of uncertainties and comparisons of economic profitability with environmental and social aspects, in order to provide for sound and sustainable judgements in regional water supply decision situations.

1.2 Aim and objectives

The overall aim of the thesis is *to develop a decision support model for assessing the economic, environmental and social sustainability of regional water supply interventions, including formations of inter-municipal cooperations.*

Specific objectives are to:

- present a generic decision support model that enables to combine fully monetized costs and benefits with criteria in the social and environmental sustainability domains;
- identify key evaluation criteria as a basis for regional assessments;
- provide a structured handling of uncertainties in input data and results; and
- evaluate the applicability of the model to aid in regional decision situations.

1.3 Scope

This thesis focuses on describing the theoretical background to the decision support model and how the aim and objectives were achieved. The concept of sustainability and its role as a driver for regionalization of the water sector is described in Chapters 2 and 3. Methods used in the proposed decision support model, i.e. multi-criteria, cost-benefit, uncertainty and sensitivity analyses are described in Chapter 4. The model development, including identification of key criteria and handling of uncertainties, as well as model application are described in Chapter 5, Paper I and Paper II. Paper I focuses on the development and application of the entire decision support model whereas Paper II focuses on the economic part of the model. The results of the work are discussed in Chapter 6 and the main conclusions of the thesis are summarized in Chapter 7.

1.4 Limitations

In the process of developing a model for supporting inter-municipal decision-making, relevant limitations of the work were needed. The main limitations of the thesis are:

- This thesis does not discuss the work procedure of generating alternative solutions to a given problem. The thesis instead focuses on how to perform sustainability assessments of already suggested alternatives.
- Economic valuations of costs and benefits can be performed in several different ways. The thesis focuses on some examples of economic valuation techniques rather than giving a broad and comprehensive economic valuation description.

2 THE CONCEPT OF SUSTAINABILITY

The concept of sustainability is used in a variety of contexts and with many different purposes. In order to develop a decision support model based on the concept of sustainability, we need to define what we mean by sustainability and with a sustainable development. This chapter gives an overview of different definitions of sustainable development and how the concept can be interpreted based on for example different ethical theories. The chapter then describes which conditions and which interpretations of the sustainability concept we have used in the development of the decision support model.

2.1 Sustainability definitions

The most commonly quoted definition of sustainable development is that of the Brundtland Report, in which it is defined as a *development that meets the needs of the present without compromising the ability of future generations to meet their own needs* (WCED, 1987). Ever since the Brundtland Report, professionals from a range of disciplines have tried to define and measure the concept of sustainability. The International Union for the Conservation of Nature defined sustainability as the *development that improves the quality of human life while living within the carrying capacity of supporting ecosystems* (IUCN, 1991).

In the scope of water services, Loucks (1997) proposed the following definition of sustainability as *those water resource systems designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity*. Gleick (2000) later defined a sustainable water use as *the use of water that supports the ability of human society to endure and flourish into the indefinite future without undermining the integrity of the hydrological cycle or the ecological systems that depend on it*. More recently, the EU-project Transitions to the Urban Water Services of Tomorrow (TRUST) defined that *sustainability in urban water cycle services is met when the quality of assets and governance of the services is sufficient to actively secure the water sector's needed contributions to urban social, environmental and economic development in a way that meets the needs of the present without compromising the ability of future generations to meet their own needs* (Brattebø et al., 2013).

A common theme in these sustainability definitions is the anthropocentric point of departure and the consideration of the future. The Brundtland Report, for example, was concerned about how actions performed today will affect the ability of future generations to meet their needs. However, as there are disagreements on what the needs of future generations will be, there are also disagreements on how sustainability can and should be achieved (Loucks, 1997). This thesis focuses on the sustainability of water supply interventions. This narrow scope allows for a distinct definition of sustainability which facilitates its quantification and hence inclusion as objective in the decision-making process. The definition of sustainability used in this thesis is introduced in this chapter, and is further described in Chapter 5.

2.2 Strong & weak sustainability

Although there are many definitions of sustainability, nearly all contain some perception of that human society and economy are intimately connected to the natural environment (Caradonna, 2014). These three components of sustainability, i.e. economic development, social development and environmental protection, which by Elkington (1997) was coined as the triple bottom line (TBL), are often seen as interdependent and equally supporting pillars of the concept (UN, 2005). The decision support model developed in this thesis is based on the three domains economy, society and environment. Figure 1 shows different models representing sustainability based on these three components.

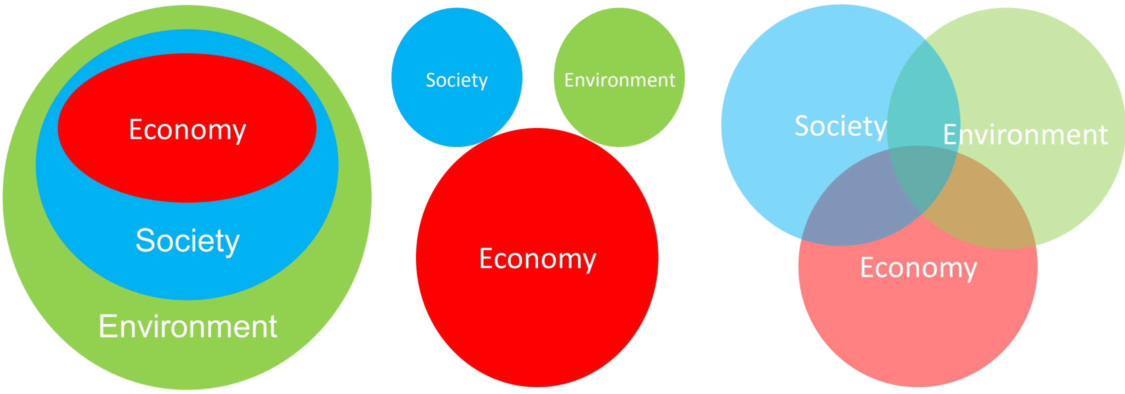

Figure 1 *Sustainability models consisting of the three pillars economy, society and environment. The Bulls' eye model (left), the Mickey Mouse model (middle) and the TBL model (right).*

In the so called TBL model, to the right in the figure, the three domains are shown as separate yet connected systems. Sustainability is defined as the common ground where the three circles converge. This model is sometimes referred to as the weak sustainability model as it tends to encourage trade-offs, i.e. assumes that a degradation in either the economic, social or environmental domain can be compensated for by improvements in one of the others (Williams, 2008). The sustainability model in the middle of the figure, usually referred to as the Mickey Mouse model, is a way of showing how the tradeoffs in TBL usually end up in reality. The economic domain is here given a much larger weight on the expense of the social and environmental domains.

According to the view of weak sustainability, sustainability is attained as long as the sum of natural and human capital does not decline (Pearce & Atkinson, 1993). There is no difference in the value provided by natural capital, such as water resources, and human-made capital, such as production plants and infrastructure, and hence they can be substituted for one another (Ang & Van Passel, 2012). Weak sustainability is here apt described by Turner et al. (1994) "*We can pass on less environment so long as we offset this loss by increasing the stock of roads and machinery, or other man-made (physical) capital. Alternatively, we can have fewer roads and factories so long as we compensate by having more wetlands or mixed woodlands or more education*".

The Bull's eye sustainability model (also called the strong sustainability model), to the left in the figure, emphasizes the environment, without which neither society nor economy can exist. In this interpretation of sustainability, economy only exists in the context of a society and is therefore seen as a subset thereof. Both society and economy are however totally constrained by the natural systems of our environment. According to the view of strong sustainability, certain environmental functions cannot be substituted by human made capital. Human and natural capitals are regarded as complements rather than substitutes (Ang & Van Passel, 2012). To achieve sustainable development, neither natural nor human-made capital may hence decline. Uncertainties about the future and risks of irreversible natural loss are arguments that support strong sustainability (Munda, 1995).

Both weak and strong sustainability have, however, shortcomings which make them hard to implement in in their purest forms. Depending on our preferences on how valuable e.g. certain natural capitals are for our well-being we will end up somewhere on the scale between the two extremes (Hedenus et al., 2015). The decision support model proposed in this thesis allows for trade-offs between sustainability domains and can hence only be used to enforce weak sustainability. The model can, however, identify whether certain alternatives lead towards strong or weak sustainability, i.e. whether there is an actual compensation between sustainability domains or sustainability criteria.

2.3 Ethical theories

In the process of developing a decision support model based on the concept of sustainability, it was important to also distinguish between different views on sustainability based on which moral ethics we embrace. This subsection gives a short overview of the two ethical theories consequentialism and deontology and describes how sustainability can be interpreted based on these theories.

In consequentialism (Anscombe, 1958), the rightness of an action is judged on the basis of its consequences. Thus, for a consequentialist, an action is morally right if its *consequences* are good, generally summarized by the saying *the end justifies the means* (Mizzoni, 2009). In utilitarianism (Bentham, 1789; Mill, 1863), which is a form of consequentialism, an action or decision is judged on the basis of its contribution to overall utility, i.e. human well-being (Sidgwick, 1981). The definition of sustainable development as put forward in the Brundtland Report, has an anthropocentric, i.e. human-centered, utilitarian perspective which focus on achieving and maintaining human well-being now and in the future (Farley & Smith, 2014; Imran et al., 2014).

In deontological ethics (Kant, 1785), actions are not judged on the basis of their consequences but on a set of principles or moral duties. It is hence our duties to intrinsic moral value principals like justice and equity rather than fulfillment of well-being that guide our actions (Howarth, 1995). In the case of sustainable development, our duty to leave an unharmed world to future generations is for example grounded in both moral intuition and formal ethical principles (Laslett & Fishkin, 1993).

Depending on which concept of sustainability and moral reasoning we adopt, the right action moving forward might differ. In this thesis we propose a decision support model based on a combination of the two ethical theories; economic consequences of alternative interventions are assessed by means of cost-benefit analysis based on impacts on human well-being, whereas social and environmental consequences are assessed based on impacts on moral principles of deontological ethics such as final[1] values of the environment (Peterson & Sandin, 2013). The decision support model then allows for weighing the economic, social and environmental domains differently, depending on the decision-makers preferences regarding sustainability.

[1] A final value is a value that something has *for its own sake* rather than as a means to something else.

3 WATER SUPPLY AND SUSTAINABILITY

This chapter gives a short background on the Swedish water supply sector and its challenges, and provides arguments from Sweden and other countries on how regionalization of the water sector may increase its sustainability. The chapter then gives a description of some advantages and disadvantages of regionalization, and continues with examples on how such advantages and disadvantages can be assessed in order to determine whether a certain strategy or intervention leads to an increased sustainability or not.

3.1 The Swedish water sector

Drinking water in Sweden is usually produced locally, and the Swedish municipalities' obligation to provide water services has traditionally emphasized a local perspective on drinking water. Sweden has also a highly decentralized planning system in which the municipalities own the physical planning of land and water use. However, there is a wide variety in land area, number of inhabitants and population density in the 290 municipalities, and, as a result, their ability to manage the drinking water provision varies significantly. For example, many challenges in the smaller municipalities are associated with a lack of competence provision, making them vulnerable to new and unexpected situations (Thomasson, 2015). Furthermore, several municipalities are facing limited financial capacities to handle present and future challenges.

Currently, about 35 percent of the Swedish municipalities operate the water supply in some form of inter-municipal cooperation (SOU 2016:32). The most common form of cooperation is inter-municipal agreements, which can be reached on almost all kinds of water cooperation, e.g. shared source waters and joint drinking water production. Joint committee is another form of cooperation, in which a committee is comprised in one of the cooperative municipalities’ organizations. The committee is not a legal entity, and each municipality is still responsible of the issues administrated thereof. Yet another form of cooperation is municipal alliances, which is a public entity responsible for the issues handed over from the member municipalities. And finally, municipalities may also form joint companies in which a board is responsible for and governs the operations. The undertakings of the company is governed by ownership directives (SOU 2016:32).

As part of a governmental initiative, the Swedish drinking water sectors was investigated between the years 2013 and 2016 with the aim of identifying current and potential challenges for a safe drinking water supply, and if necessary propose appropriate measures. The inquiry (SOU 2016:32), points at several challenges for the Swedish water providers, including an ageing infrastructure and predicted increases in chemical and microbiological health hazards. In addition, several water providers are suffering from limited financial and personnel resources, reducing their ability to handle the challenges accordingly. In order to achieve economic, technical and competence stability and to uphold a sustainable water supply, the inquiry concluded that an increased regionalization is necessary for the Swedish water sector.

3.2 Regional water services

Similar to the Swedish conclusions in SOU 2016:32 , regional cooperation is recommended in several countries as a means to tackle present and future challenges and achieve sustainable water services. In the US, the American Water Works Association (AWWA, 2015) emphasizes that regional cooperation is a valuable tool for the utilities to provide safe and reliable water services to their customers in a sustainable way. They highlight benefits such as knowledge sharing, increased efficiency, minimized capital expenditure and enhanced source water protection; and they conclude that a successful cooperation should be structured to enhance service, achieve balance between responsibility and authority, and equitably account for all parties involved. In Germany, the German Bundestag (2006) states that regional cooperation is a key element when modernizing infrastructure, and argues that cooperation is a basis to ensure long-term safety, reliability and sustainability in the water sector.

The main drivers for regionalized water systems, as put forward in Figure 2, are typically the potentials of increased efficiency through economies of scale, improved access to water resources, enhanced professional capacity, integrated water resource management, access to finance and private sector participation, and cost sharing between higher and lower cost service areas (Frone, 2008).

However, the above mentioned benefits are strongly dependent on the context and can hence not be taken for granted (Kurki et al., 2016). Furthermore, there are also recognized disadvantages and challenges associated with regionalization, which policy- and decision-makers need to take into account for proper evaluations of reform proposals. Some advantages and disadvantages are summarized in Table 1 and Table 2 based on Frone (2008) and SOU 2016:32 , respectively. A few of these aspects are described further in the sub-chapters below.

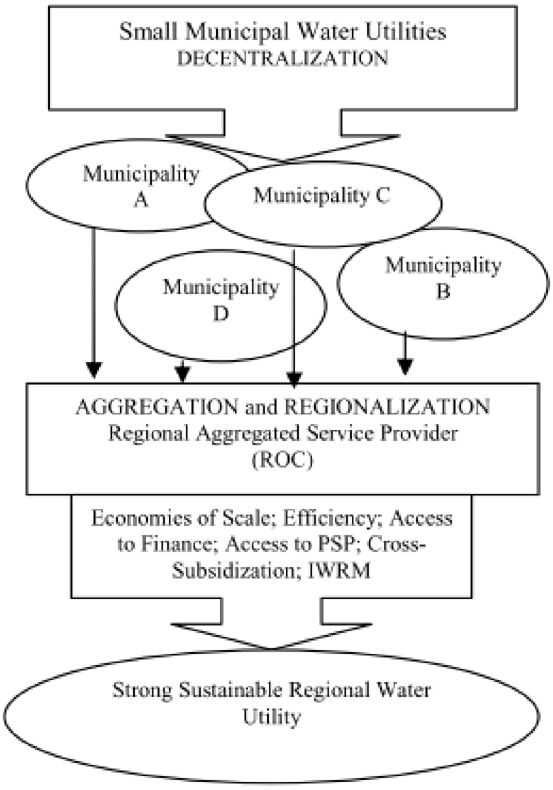

Figure 2 *Regionalization of water utilities (Frone, 2008)*

Table 1 *Potential benefits and constraints of regionalization (Frone, 2008)*

Administrative aggregation and regionalization of water service providers	
Potential benefits	**Potential constraints**
Economies of scale in procurement and support functions; economies of scale in designing works for neighboring towns	Existing installations may limit potential for efficiency gains as they cannot be redesigned; resistance from labor against staff reductions
Better and easier access to water resources in water scarce areas	Lack of incentives to share water; sharing of water access would lead to tariff increase for water-rich municipalities
More integrated approach to water resources management	Administrative boundaries are often not aligned with river basin boundaries; conflicts and lack of coordination between water users
Enhanced professional capacity through transfer of management, technical know-how and expertise	Lack of local recognition of a need for support and potentially higher costs from external support; distance between population centers
Access to banking finance and international donors	Higher risk for municipalities due to joint liabilities for the loans
Access to private sector participation; can be combined with economies of scale to dramatically improve efficiency of operations	Participation of the private sector for the provision of utilities may generate popular and political resistance
Cost sharing between high- and low-cost service areas	Resistance of communities with lower costs to subsidize those with higher costs

Table 2 Pros and cons with municipal and regional responsibility of water supply in Sweden (SOU 2016:32)

Aspect of water supply	**Municipality advantages**	**Municipality disadvantages**	**Regional advantages**	**Regional disadvantages**
Planning	Links to other municipality plans	Missing regional perspective	Links to a regional developmental responsibility	Comprehensive task
Financing	Local and participatory	Vulnerable in small municipalities, high taxes	Economies of scale, larger and more robust base of tax-payers	Difficult for consumers to participate and have influence
Competence provision	-	Difficulties in small municipalities	Economies of scale, facilitates strategic work	New experiences may need to be established
Operation	Local knowledge	Vulnerable in small municipalities	Economies of scale, can cope with the future	New experiences may need to be established
Backup systems and redundancy	-	Inter-municipal cooperation is often a pre-requisite	Economies of scale, flexibility	-
Emergency preparedness	Local knowledge, principle of subsidiarity, participation, responsibility	Consumers in small municipalities are exposed	Economies of scale, links to other regional responsibilities, e.g. health	-

3.2.1 Economies of scale

As water supply provision is associated with large capital costs and, in many countries, a responsibility of municipalities, the services do not experience market competition. The absence of market competition tends to result in inefficiency, which in turn affects the drinking water consumers with e.g. higher prices and/or poorer service quality (Carvalho & Marques, 2016). One way to rectify cost inefficiency is by exploiting economies of scale, i.e. the cost advantage that may arise of an increased production. Scale economy is one of the major drivers of regionalization, and a significant number of studies have been investigating scale (dis)economies in the water sector. The most frequently used method to evaluate efficiency has been the econometric approach to estimate cost functions (Abbott & Cohen, 2009). Even though the studies use a variety of evaluation methods and output measures, there is generally a consensus that the water sector has important economies of scale up to a certain output level after which diseconomies of scale appear (Carvalho & Marques, 2016; González-Gómez & García-Rubio, 2008; Saal et al., 2013). Countries with excessive fragmentation, such as Germany and Portugal, may benefit economically from merging utilities whereas countries with a high degree of consolidation, such as UK and the Netherlands, may cause increased costs if merging further (Saal et al., 2013). The optimal scale, however, is found to vary between countries and over time (Nauges & van den Berg, 2008). For overview of scale economy studies, see for example Abbott and Cohen (2009), Martins and Fortunato (2016) and Sjöstrand (2017).

3.2.2 Shared water resources and facilities

Ensuring access to sufficient amount and quality of source waters is another driver for regionalization. The potential of sharing unevenly spaced water resources can be particularly obvious in water scarce areas or areas with insufficient water quality, where management of the water systems may need to be carried out at a regional scale in order to ensure water safety and reliability. A predicted shortage was for example one of the drivers leading to the establishment of 10 Regional Water Authorities in England and Wales in 1974 (Okun, 1975). Water scarcity in the coastal zones was also a main driver when regional wholesale water companies were formed in Finland (Kurki et al., 2016). By connecting several municipal systems into a regional water supply system, each municipality may benefit from having access to multiple source waters and treatment plants in the event of failure of any particular one (Palaniappan et al., 2007).

3.2.3 Professional capacity

Ensuring competence provision, with access to sufficient and right skilled personnel, is another major driver for regionalization. Even though small municipalities usually have enough personnel for routine activities, they are often short of staff to perform highly skilled operating and management activities (Frone, 2008; Schmidt, 2014). Many challenges in smaller municipalities are associated with the lack of personnel, which also makes them vulnerable to new and unexpected situations (Thomasson, 2015). Larger organizations are often seen as more attractive employers due to their career opportunities (Thomasson, 2013). Hence, transforming to larger, regional organizations may increase the chances to hire and retain highly skilled personnel (Frone, 2008; Kurki et al., 2016; Lieberherr, 2011). A larger organization also tends to facilitate exchange of experience within the organization as well as pooling of personnel between the municipalities (Lieberherr, 2011). There is, however, a risk of losing local knowledge when transforming from a local to a regional organization (Kurki et al., 2016).

3.2.4 Autonomy and legitimacy

The organizational autonomy, i.e. the separation of political decision-making from operational and management decisions, varies between the different forms of inter-municipal cooperations. Inter-municipal agreements are expected to have the lowest degree of autonomy since it is operated through municipal utilities by political decision making. An inter-municipal company is argued to have a higher degree of autonomy than an alliance (Kurki et al., 2016). As autonomization means that the direct voter input decreases, it is argued to undermine democratic structures by weakening democratic legitimacy requirements such as accountability, responsiveness and governability (Lieberherr, 2011).

Lieberherr (2011) found a positive correlation between autonomization and a utility's performance in terms of 1) clarifying roles and responsibilities, 2) an increase in professional management with more strategic planning and flexibility, 3) improved internal interactions in terms of adjustment flexibility, and 4) increasing sustainable practices. There was, however, a negative relationship between autonomization and transparency as the public sphere had less oversight and control. Kurki et al. (2016) found that the decision-making process was more efficient and less bureaucratic in the more autonomous organizations. However, citizens acknowledged that the decision-making in a water company could move too far away from democratic structures.

3.3 Assessing water supply sustainability

The performance of water utilities depends largely on their abilities to deliver a continuous supply of good quality drinking water. To be able to assess whether a suggested intervention is likely to move the system towards or away from sustainability, its social, economic and environmental consequences need to be evaluated. There is, however, no widely established method to assess sustainability of water services (Marques et al., 2015). Evaluation methods such as multi-criteria decision analysis, cost-benefit analysis, life cycle assessments, and optimization techniques have all been used to evaluate sustainability in the water sector.

In order to assess sustainability, a defined set of sustainability performance measures, i.e. evaluation criteria, is required (Foxon et al., 2002). In the research literature, a significant number of sustainability criteria have been proposed for the water sector. In Table 3, criteria used in water supply and demand management studies between 2000 and 2016 are summarized (Rathnayaka et al., 2016). From this literature review, Rathnayaka et al. (2016) concluded that of the environmental, social and economic criteria, social sustainability is given the least attention in literature. They also recognized that most water sustainability literature lack inclusion of cost externalities.

Table 3 Evaluation criteria utilized in literature to assess sustainability of water supply and demand management options. From Rathnayaka et al. (2016).

	Objectives	**Evaluation criteria**
Environmental criteria	River and waterbody health	Quality of waste water produced and their impacts (contribution to acidification and eutrophication, effects on flora and fauna) Quantity of wastewater produced Storm water runoff
	Maintain river, local creaks, and	Effect on environmental flow and surface water Freshwater/portable water saved

	wetlands	Effects on groundwater level and pattern (ground water infiltration, recharge, and depletion)
	Protect land ecosystem	Effects on fauna and flora/biodiversity Effects on habitats and protected natural habitat area Land cover change effects (e.g. habitats affected) Solid waste quantity and quality (e.g. sludge)
	Protect atmospheric ecosystem	Greenhouse gas and other emissions Photochemical oxidant formation Other pollutants (e.g. dust, noise)
	Efficient resource use	Energy use and recovery Ability to use renewable energy source(s) Fresh water use Land use Materials for construction Chemical use Reuse and recycling of resources
Social criteria	Ability to meet user acceptance	User acceptance in terms of water quality Willingness to accept demand management options Acceptance of increase/decrease in water bill User awareness and involvement
	Ability to meet community acceptance	Recreational values (visual amenity) Impacts on urban heat island effect Provision of educational opportunities Small scale flood mitigation benefits Odor/pests—any other negative impacts on the local community Number of jobs it creates
	Health and hygiene	Safety (number of incidents/accidents) Risk of infections (number of outbreaks/people affected) Risk of other health hazards (presence of carcinogenic compounds in influent water) Exposure to toxic components (Cd, Hg, Pb) in operation
	Political approval	Project duration (e.g. design and construction phase) Management/institutional effectiveness and efficiency Uncertainty of volume, timing, cost, approval, and delivery State of readiness (availability of institution, documents, policy) Ability to meet environmental or other regulations
Economic criteria	Total direct cost	Capital cost Maintenance cost Operational cost including energy and other costs Disposal cost Cost of water distribution-construction, maintenance, and operation Cost of water storage—construction, maintenance, and operation
	Total indirect cost	Value of hydropower/energy and other byproducts, such as fertilizer
Risk-based criteria	Reliability	Probability of supply shortfalls (chance of not meeting the expected production)
	Vulnerability	Magnitude of failure
	Resilience	Failure duration or how quickly system returns to its satisfactory state after a failure
	Robustness	Ability to perform satisfactorily under a range of system changes (e.g. climate)

Functional criteria	Flexibility of the option	End-uses it can fit Flexibility in scaling Capacity/Yield Potential for growth
	Construction flexibility	Challenges with management of site (presence of contaminated soil and underground services) Ability to blend with available supplies/infrastructure
	Operational and maintenance flexibility	Ease of maintenance including monitoring frequency based on water quality and quantity Technical knowledge needed in handling the system
	Durability	Life span of the water supply infrastructure/option
	Interactions between the system components	Effects on sewer distribution network such as sewer blockage, odor, and corrosion Effects on drainage distribution network Effects on water supply network (e.g. size of pipe)

The number of criteria should be kept as low as is consistent with making a well-informed decision regarding the interventions at hand and their effect on the social, environmental and economic sustainability domains. The selection of appropriate criteria is, amongst other things, dependent on the scale of the intervention, e.g. if it is on a local, regional or national level (Mihelcic et al., 2003). On the inter-municipal level, the focus in research literature has mainly been on assessing one specific or a very small number of criteria. As mentioned previously, there are for example studies focusing on scale economies of joint production (Carvalho & Marques, 2016; González-Gómez & García-Rubio, 2008; Saal et al., 2013), and studies focusing on assessing how regionalization affects the performance of water governance in terms of democratic legitimacy (Kurki et al., 2016; Lieberherr, 2011). There is, however, an absence of studies taking a comprehensive approach on the inter-municipal level to assess water supply interventions so that both positive and negative social, economic and environmental effects can be evaluated and weighted against each other to constitute decision support.

4 METHODS

This chapter gives a theoretical background on methods used in the developed decision support model, i.e. cost-benefit, multi-criteria, uncertainty and sensitivity analyses.

4.1 Cost-benefit analysis

Cost-benefit analysis (CBA) was used in the decision support model to evaluate the economic sustainability domain. CBA is a structured method to compare societal costs of an intervention with its benefits, see the different steps of the analysis in Figure 3. CBA is often used as a decision-support tool to e.g. compare and rank alternative interventions and analyze whether they are economically beneficial or not (Johansson & Kriström, 2016). The benefits and costs, which are defined as increases and reductions in human well-being, are as far as possible measured in monetary terms.

The decision-metric of the CBA is the net present value (*NPV*), calculated as

$$NPV_a = \sum_{t=0}^{T} \frac{B_{a,t}}{(1+r_t)^t} - \sum_{t=0}^{T} \frac{C_{a,t}}{(1+r_t)^t} \tag{1}$$

where a is the alternative intervention, t is the time when benefit or cost occur, T is the time horizon, r_t is the discount rate at time t, C are the costs and B are the benefits in relation to the reference alternative.

An intervention is considered economically profitable when its total benefits to society are larger than its total costs to society, i.e. when its *NPV* is positive. The society in this meaning is the sum of individuals for which the CBA is performed, i.e. the aggregated willingness to pay (WTP) for benefits and willingness to accept (WTA) compensation for losses.

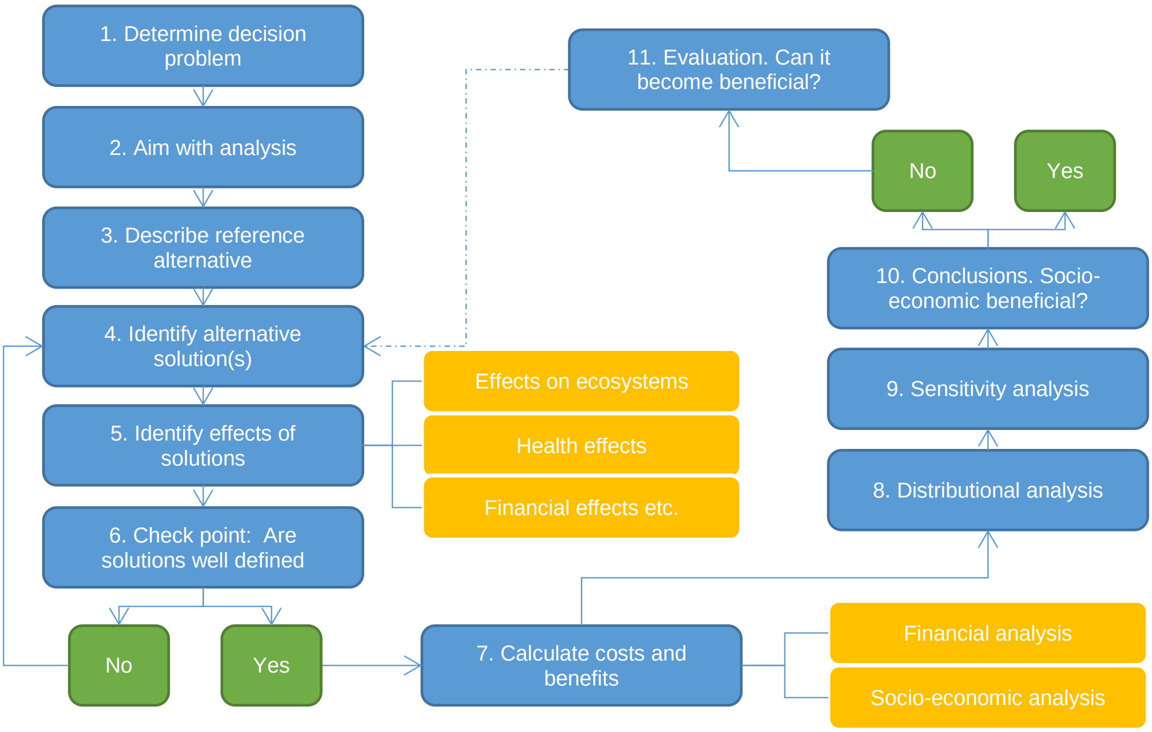

Figure 3 CBA step by step. Adapted from Kriström and Bonta Bergman (2014).

Preferably, all costs and benefits included in a CBA are quantified in monetary terms. There are several economic valuation methods based on welfare theory to estimate these values. The methods are often grouped in the main categories: direct market valuation methods, revealed preference methods and stated preference methods (Bouma & van Beukering, 2015), see examples of valuation methods in each category in Figure 4.

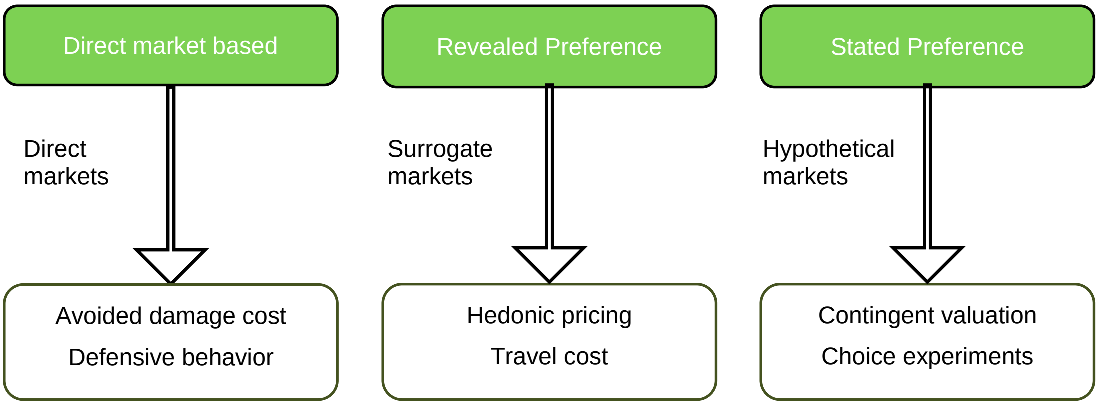

Figure 4 Economic valuation approaches.

In direct market based methods, prices from well-functioning markets provide information on the economic values. The avoided damage cost and the defensive behavior methods are examples of direct market based approaches. In the defensive behavior method, WTP is derived from measuring individuals' costs for avoiding a negative effect, e.g. consumer's expenditure on water bottles to avoid polluted tap water. In damage cost methods, WTP is estimated by measuring the resource costs incurred by the negative change, including both direct and indirect costs. Direct costs are for example costs of medical visits due to polluted drinking water, whereas indirect costs reflect opportunity costs of e.g. reduced production (Yong & Loomis, 2014).

Revealed preference methods (Bockstael & McConnell, 2006) rely on individuals' expenditure choices on market goods and services to assess their WTP to related non-market goods and services. Two commonly used revealed preference methods are the travel cost method and the hedonic pricing method. The travel cost method is typically used to value sites that are used for recreation. Individuals' cost incurred in reaching the site is used as a value for the site, or for the water quality of the site assuming the water quality is a decisive factor for the travel behavior. The hedonic pricing value method uses differences in property pricing to estimate individuals' values on e.g. nearby water resources (Yong & Loomis, 2014).

Stated preference methods use structured questionnaires to estimate individuals' values of goods and services not commonly traded on existing markets. The contingent valuation method and the choice experiment method are two frequently used stated preference methods. In the contingent valuation method, individuals are asked directly what they would be willing to pay to obtain a specified good (or willing to accept to give up the good). In choice experiments, individuals are presented with consequences and costs of alternative interventions and are asked to rank the interventions or choose the most preferred one. The rankings or choices are then analyzed to determine their WTP for different interventions (Freeman et al., 2014; Yong & Loomis, 2014).

When primary economic valuation studies are considered too expensive or infeasible to conduct, estimates of benefits and costs can be provided using benefit transfer. The benefit transfer approach makes use of previously performed valuation studies from another area and extrapolates the economic values to the area for which a valuation is required. Benefit transfer is usually considered a second-best solution, but is the only means to provide empirical economic information when time, funding or other constraints prevent the use of the above mentioned methods (Johnston et al., 2015).

When a multi-year analysis is performed, the costs and benefits must be measured in real values (constant prices) instead of nominal values (current prices). Thus, the costs and benefits are discounted using specified discount rates. There is an extensive literature on the subject of discount rates. There is, however, no objective and collectively acknowledged rate to be used in a CBA. The choice of discount rate is instead one of the most disputed subjects of economic theory (Munda, 1995). It illustrates how we value e.g. equity between generations, and environmental resources versus capital resources. A low discount rate suggests that we are more interested in, and willing to pay for, the welfare of future generations compared to a higher rate. Lower discount rate generally results in more interventions receiving positive *NPV*s, and hence, a greater portion of our wealth will be invested rather than consumed (Gollier, 2011). To increase the weight devoted to the welfare of future generations, some studies have suggested declining discount rates (Gollier et al., 2008). Within the Stern Review on the Economics of Climate Change, an average discount rate of 1.4 % was applied (Stern, 2006). The Swedish Transport Administration recommends a discount rate of 3.5 % to be used in publicly provided infrastructure investments (ASEK, 2018). Whichever discount rate is chosen, it is important to remember that the choice has ethical and moral implications, and it can very much influence the CBA results.

4.2 Multi-criteria decision analysis

Multi-criteria decision analysis (MCDA) is a general decision support framework commonly used in complex decision problems to synthesize a variety of information and compare alternatives with significantly different impacts (Figueira et al., 2005). MCDA can be used to integrate quantitative, semi-quantitative and qualitative information concerning alternative interventions. It provides a structured approach in decision situations where stakeholder participation is central and where it is necessary to make use of the decision-maker’s preferences to distinguish between the alternatives. Large emphasis is placed on the judgement of the decision-making team and involved stakeholders to establish objectives and criteria, to assess the relative importance between the criteria, and to decide whether trade-offs between criteria are allowed or not. There is only a limited number of non-compensatory techniques to use if trade-offs are not acceptable, whereas several different MCDA techniques can be used if compensation is allowed. The main steps normally included in an MCDA are presented in Table 4.

The first two steps focus on determining the decision context, objectives, and stakeholders, as well as defining alternative solutions that might meet the goals and objectives. Once that is settled, the evaluation criteria need to be determined. The criteria serve as performance measures in the MCDA, and hence, they need to be operational so that an expert judgement or a data measure can state how well an alternative perform in relation to a specific criterion. The criteria must also be set up to avoid double counting and they must be independent of each other, so that a judged performance of one alternative on one criterion is independent of its judged performance on another criterion.

Table 4 Main steps of MCDA. Adapted from DCLG (2009).

Step	Description
1	Establish the decision context. a) Establish aims of the MCDA, and identify decision makers and other key players. b) Design the socio-technical system for conducting the MCDA. c) Consider the context of the appraisal.
2	Identify the alternative interventions to be evaluated.
3	Identify objectives and criteria. a) Identify criteria for assessing the consequences of each alternative. b) Organize the criteria by clustering them under high-level and lower-level objectives in a hierarchy.
4	'Scoring'. Assess the expected performance of each alternative against the criteria. Then assess the value associated with the consequences of each alternative for each criterion. a) Describe the consequences of the alternatives. b) Score the alternatives on the criteria. c) Check the consistency of the scores on each criterion.
5	Weighting'. Assign weights for each of the criterion to reflect their relative importance to the decision.
6	Combine the weights and scores for each alternative to derive an overall value. a) Calculate overall weighted scores at each level in the hierarchy. b) Calculate overall weighted scores.
7	Examine the results.
8	Sensitivity analysis. a) Conduct a sensitivity analysis: do other preferences or weights affect the overall ordering of the alternatives? b) Look at the advantage and disadvantages of selected alternatives. c) Create possible new alternatives that might be better than those evaluated.

Each alternative is then evaluated by scoring it on each criterion, either qualitatively or quantitatively. The scores are measures of the performance of the alternatives with respect to each criterion. The scoring can be made in either absolute or relative terms. The developed model in this thesis uses relative scoring in relation to a reference alternative. To score the alternatives' performance, the criteria need some sort of performance scales. The criteria measures might originate from a natural scale, i.e. based on their original units such as kg/m^3, or from a qualitative scale, e.g. ranging from very low to very high performance. If the criteria are measured on different scales, a unified scale is needed in order to compare and combine the scores. A common way to establish a unified scale is to remap the measures onto an interval scale, e.g. from 0 to 100. This interval scale needs to be defined by two reference points for each criterion, usually the min and max values. There are two different ways to determine these reference points, i.e. either by local scaling or global scaling. A local scale uses the alternative interventions at hand to determine the min and max values of its scale, i.e. the *best (worst) performing alternative* is remapped to e.g. 100 (0) in the local scale. In a global scale, on the other hand, the *best (worst) possible performance,* according to decision-makers' and experts' experience, define its max (min) values, e.g. so that 0 represents the worst possible performance and 100 represents the best possible performance. The decision-makers and involved experts are hence responsible for determining the endpoints in the global scale (Monat, 2009).

The scores can be assigned to the alternatives in three different ways: by using a value function to transform a measurement of the specific criterion to a score; by direct rating using expert opinions and judgements to assess the alternatives performance; or by pairwise assessments by experts on how each alternative perform relative to the other alternatives (DCLG, 2009).

Each criterion is then assigned a weight, reflecting that criterion's relative importance for the decision problem to the other criteria. The weighting procedure, hence favor some criteria more heavily than others. One weighing procedure is the swing weighing method, which is based on comparisons between criteria. The weight of a criterion reflects the decision-makers' perception of how important that criterion's swing in values (i.e. the range difference between the worst and best alternatives) is compared to the swing in values of the other criteria. Another weighting method is called importance weighting, which is the method used in the developed model in this thesis. Importance weighting is based on the decision-makers' perception of how significant a particular criterion is compared to the other criteria (Monat, 2009).

The weights and scores are then combined to give an overall assessment of each alternative. This can be performed as a product, an average or a function. The most commonly used method, and the one used in the proposed decision support model, is to calculate the weighted average of the scores (DCLG, 2009). A sensitivity analysis is then used to assess how the ranking is affected by different weighting and scoring.

4.3 Uncertainty and sensitivity analyses

Uncertainties from a number of different sources may exist in sustainability assessments of alternative interventions. Uncertainties are often categorized as either aleatory or epistemic (Kiureghian & Ditlevsen, 2009). An epistemic uncertainty is one that is caused by lack of knowledge or data, and can hence be reduced by e.g. gathering more data. An aleatory uncertainty is one that is caused by the natural randomness of a phenomenon or experiment and is not possible to reduce.

Uncertainties can be estimated by e.g. computing a standard deviation from a sample of measurements or by creating an estimate based on experience. Probability distributions can then be used to represent the uncertainties. Probability distributions are functions describing the relationship between the outcome and the frequency of its occurrence. There are many different types of probability distributions representing varying characteristics of data distributions, see Figure 5.

In the proposed decision support model, lognormal probability distribution functions were used to represent uncertainties in economic cost and benefit values, and Beta PERT distribution functions were used to represent uncertainties in social and environmental scores.

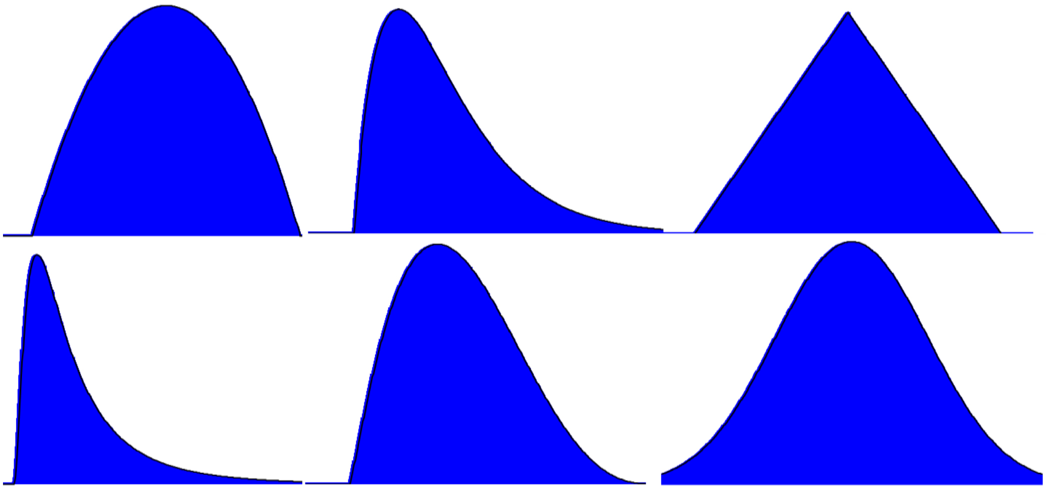

Figure 5 *Examples of how a few probability distributions can look like. Some of them can however also look very different compared to what is shown here. From top left to low right: Beta, Gamma, Triangular, Lognormal, Beta PERT and Normal distributions.*

Monte Carlo simulations can then be used to perform the calculations needed in an assessment, e.g. calculations of net present values or weighted average of scores including uncertainties. A Monte Carlo simulation samples values randomly from the input probability distributions and then calculates results over and over, involving thousands or tens of thousands of recalculations (iterations), each time with a different set of random values. The simulations produce probability distributions of the possible outcomes. This is beneficial since it not only provides information regarding the magnitude of e.g. the net present values, but also regarding how likely each outcome is. As an example, Figure 6 shows the results of *NPV* calculations for the two fictive alternatives A and B. The B alternative has a higher mean *NPV* value and would probably be seen as the most economically beneficial alternative if the mean values were the only information at hand. However, the uncertainties regarding the *NPV* estimates are larger for B than for A, and so is the probability that the *NPV* will be negative. Depending on if the decision-maker is willing to take risks or not, the final decision of which alternative to choose might differ. The information from the Monte Carlo simulation can hence help decision-makers make a more informed decision on which alternative to choose.

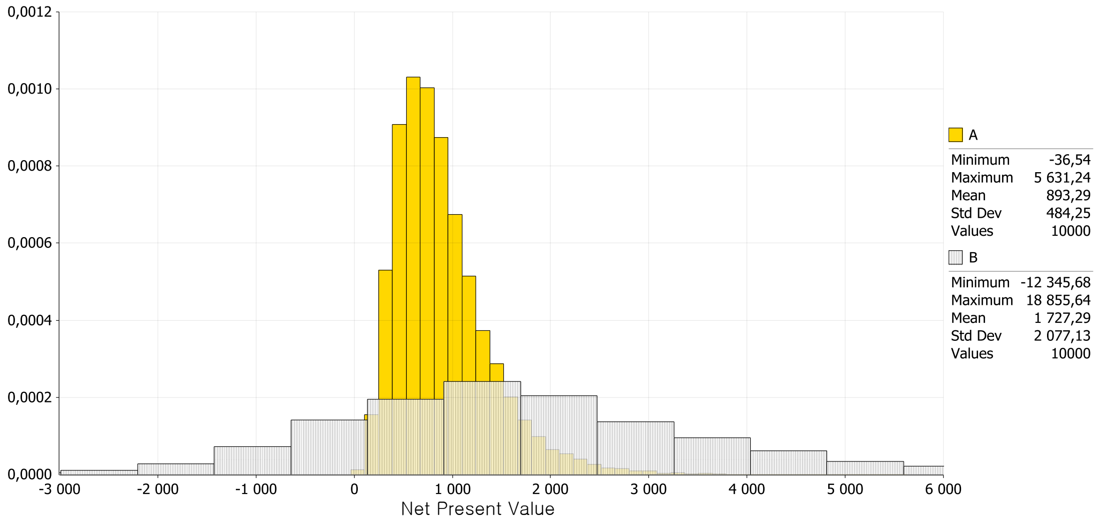

Figure 6 Histograms showing the outcomes of alternative A and B.

One of the many advantages with Monte Carlo simulations, is that the data generated can easily be presented graphically, facilitating communications with decision-makers and stakeholders. Figure 7 shows the same result as Figure 6, however presented as cumulative probability distributions, typically used to determine the probability to fall below a certain critical value.

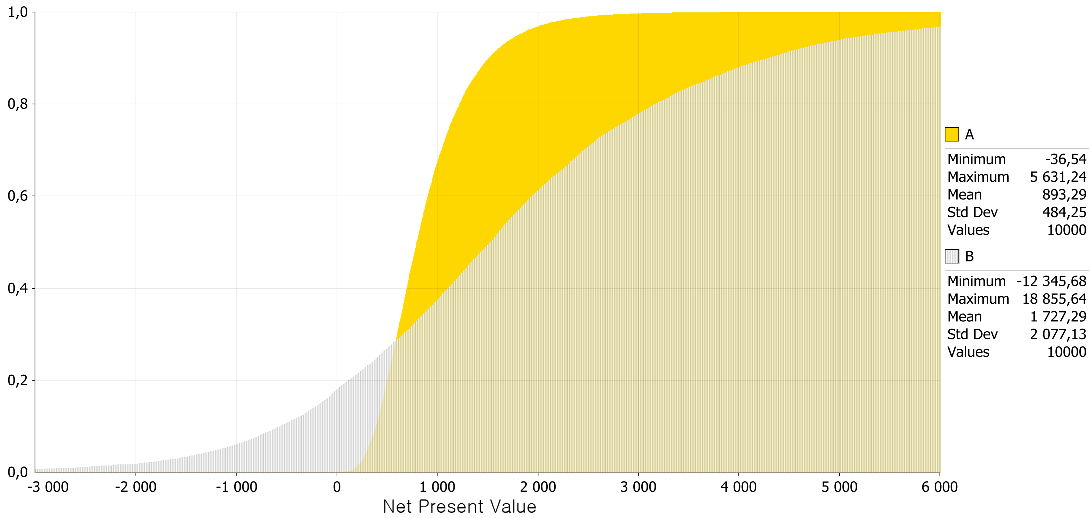

Figure 7 Cumulative probability of alternatives A and B.

Monte Carlo simulations can also be used to perform sensitivity analyses. Sensitivity analysis refers to the variation in results due to changes in input values, and can be used to provide a ranking of the input values based on their contributions to outcome uncertainty and variability. This information can then be used to support decisions on which input values to prioritize for further research and/or data collection in order to reduce uncertainties. These decisions should generally take the most influential input values into consideration and the cost of gaining new information. The sensitivity analysis can be important to determine the expected value of information thereof. The sensitivity can be analyzed and displayed in a number of different ways. Figure 8 gives an example of sensitivity analysis, showing Spearman's rank correlation coefficients for input values of different sustainability criteria. The correlation values can vary from -1 to 1. A value of 0 means that there is no correlation between the input value and the result, whereas a value of 1 (-1) means a perfect positive (negative) correlation. The sensitivity analysis hence shows the importance of the different input values.

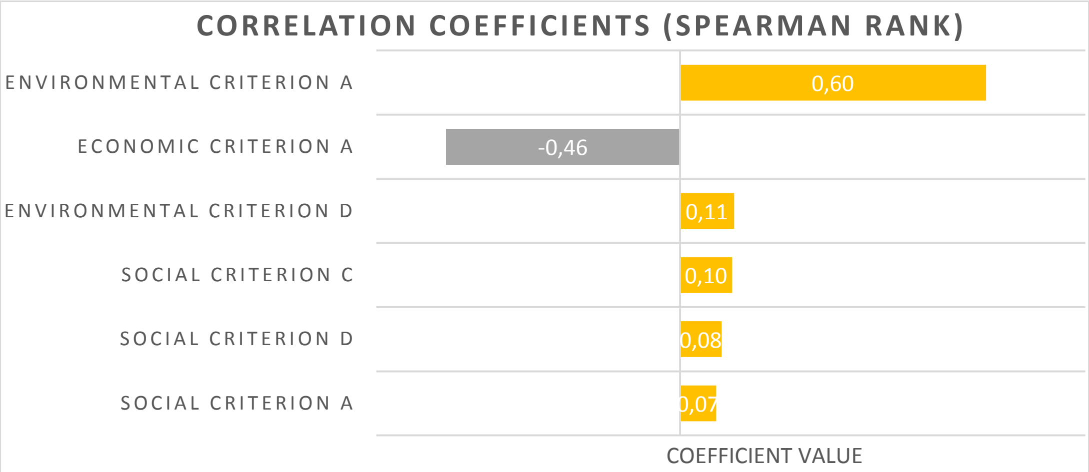

Figure 8 *Example of correlation coefficients of input values.*

5 SUGGESTED DECISION SUPPORT MODEL

This chapter presents the suggested decision support model for sustainability assessments and its application in the Göteborg region in Sweden.

5.1 Model development

A decision support model for sustainability analysis of regional water supply interventions can be based on a variety of different methods and assessment techniques. In order to develop the model and select suitable evaluation methods, a set of model requirements were defined. The model should be able to:

- take different sustainability viewpoints into account (Chapter 2);
- provide a generic gross set of sustainability criteria (Chapter 5.1)
- provide separate analyses of the social, economic and environmental sustainability domains (Chapter 4.1, 4.2, and 5.1);
- combine monetized economic effects with non-monetized social and environmental effects for integrated analysis of all three sustainability domains (Chapter 5.1);
- include uncertainties of estimates (Chapter 4.3);
- include stakeholder preferences (Chapter 4.2); and
- analyze results over long time horizons (Chapter 4.1 and 5.1)

Based on the above requirements, a combination of cost-benefit analysis and multi-criteria decision analysis were selected as a basis for the model. A probabilistic approach was chosen, in which probability distributions represented uncertainties of estimates and Monte Carlo simulations were used for uncertainty and sensitivity analysis.

The development of the model included: a literature review on water supply decision-making, decision support methods, sustainability criteria and effects of regionalization (Sjöstrand, 2017); stakeholder workshops to identify generic sustainability criteria and economic costs and benefits for regional interventions; adjustment of chosen methods to fulfill the above requirements; and a case study application to test, evaluate and illustrate the use of the model in a real-world situation. The decision support model was developed in Paper I and is summarized in this chapter. The main components of the model are presented in Figure 9.

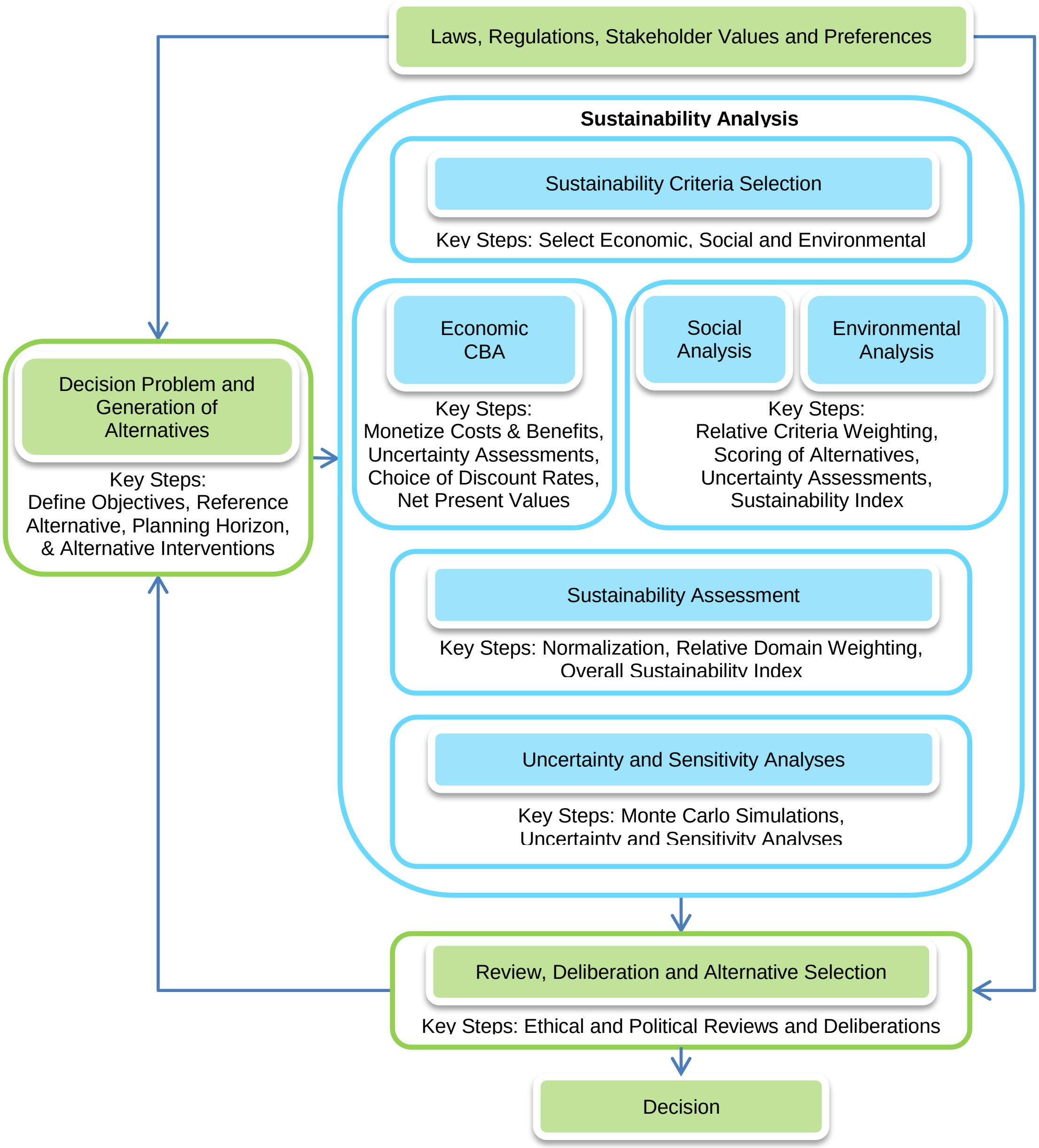

Figure 9 *Schematic description of decision support model for sustainability assessments.*

5.1.1 Sustainability criteria

A generic list of sustainability criteria was developed, representing the social, environmental and economic sustainability domains (Table 5). The criteria list was based on the literature review Sjöstrand (2017), and modified by prioritizations from stakeholders in the Göteborg region in Sweden. As mentioned in chapter 2, the economic domain reflects a utilitarian approach, while the other criteria relate to the deontological approach.

Table 5 Generic set of sustainability criteria.

Domains	Criteria	Description
Social	Equity	Effects on equity regarding if some consumers and/or municipalities are made worse off by the alternative.
	Health	Effects on human health due to insufficient source water quality, quantity, water treatment, distribution and/or emergency preparedness.
	Consumers' trust	Effects on consumers' trust in the water providers.
	Access and participation	Effects with regard to public access and participation in water supply planning and decision-making.
Environmental	Energy use at construction	Total energy use at construction.
	Energy use at production and distribution	Total energy use at production and distribution.
	Water use	Effects on water use in production and distribution, e.g. water reuse, alternative water use and leakage.
	Materials for construction	Use of non-renewable materials for construction.
	Chemical use	Effects on total chemical use in water production.
	Non-recyclable waste	Production of non-recyclable waste.
	Aquatic ecosystems	Effects on aquatic ecosystem viability due to quality and/or quantity changes in water resources.
	Terrestrial ecosystems	Effects on terrestrial ecosystem viability due to e.g. land use changes.
Economic	Economic profitability	Economic profitability assessed by means of CBA.

5.1.2 Economic analysis

The economic domain of the model is evaluated by means of CBA and calculations of *NPV,* as described in chapter 4.1. A generic list of costs and benefits (Table 6), was developed based on direct and indirect costs and benefits commonly assessed in the water sector, and on costs and benefits argued to be missing in assessments of water supply alternatives (Rathnayaka et al., 2016; Sjöstrand, 2017). Paper II shows how some of the key costs and benefits can be estimated and valued in monetary terms, giving a special focus to valuations of effects on consumers' health, water supply reliability, and operation and maintenance (O&M) costs. The choice of discount rate and time horizon to be used in the analyses is determined by the decision-making team for each new assessment.

Table 6 Potential cost and benefits items due to regional water supply interventions.

Cost and benefit items	Description
Water utility costs and benefits	Investments Operational and maintenance costs Other costs and benefits
Water supply reliability effects	Lost value added in economic sectors Losses for residential consumers
Water related health effects	Costs for healthcare Lost production Risk assessments reflecting discomfort and loss of life
Effects on ecosystem services	Drinking water Irrigation Hydropower Industrial water use Recreational activities Flood & erosion risk reduction Retention of contaminants Other water services
Effects on agriculture, forestry and industry due to water protection restrictions	Agricultural, forestry and industrial production Other effects on agriculture, forestry and industry due to water protection restrictions

5.1.3 Social and environmental analyses

The social and environmental domains are evaluated by the MCDA procedure of scoring and weighting described in chapter 4.2. The model applies:

- relative scoring, i.e. the scoring is made in relation to a reference alternative;
- global scale, i.e. the alternatives are assessed on a scale from -10 to 10 in which 10 (-10) reflects the best (worst) possible performance according to the decision-makers' and experts' experience, 0 reflects the same performance as the reference alternative, and minus (plus) values hence represent deterioration (improvement) compared to the reference alternative;
- direct rating, i.e. the alternatives' performance are assessed by expert and stakeholder opinions and judgements;
- importance weighting, i.e. the weight of a criterion reflects the decision-makers' perception of how significant that criterion is compared to the other criteria for the specific decision problem; and
- linear additive technique, i.e. calculating a weighted average of the scores as shown in Equation 2 below.

Calculations of environmental and social sustainability index, S_{Env} and S_{Soc}, are given by

$$S_{d,a} = \sum_{k=1}^{K} w_k z_{a,k} \tag{2}$$

where *a* is the alternative, *d* is the domain, and *w* is the weight and *z* is the score for each criterion *k*. The sustainability index can thus vary between -10 and +10, representing overall deterioration or improvement in the specific sustainability domain relative to the reference alternative.

5.1.4 Overall sustainability

Alternatives can now be ranked for each sustainability domain, by the sustainability indexes in the environmental and social domains and by the *NPV*s in the economic domain. In order to calculate an overall sustainability index, all domains need to be comparable and assessed on a common scale. In the model, this is accomplished by normalizing the economic domain by ratio normalization, by the absolute maximum value of the 5th and 95th percentiles of all *NPV*s, and by scalar multiplication by a factor 10 (Paper I). The economic domain is hence adjusted to a scale from -10 to 10. The overall sustainability index (S) is then calculated for each alternative (a) by

$$S_a = W_{Env} S_{Env,a} + W_{Soc} S_{Soc,a} + W_{Eco} S_{Eco,a} \tag{3}$$

where W is the relative weight of each domain, S_{Env} and S_{Soc} are the environmental and social sustainability indexes, and S_{Eco} is the normalized *NPV* given by

$$S_{Eco,a} = 10 \frac{NPV_a}{Max\left(\left|P05(NPV)\right|,\left|P95(NPV)\right|\right)} \tag{4}$$

5.1.5 Uncertainty and sensitivity analyses

The lognormal probability distribution was chosen to represent uncertainties of estimated costs and benefits. The lognormal distribution is commonly used in economics and cost analysis (Garvey et al., 2016). It is closely related to the normal distribution, i.e. log-normalized data is normally distributed if the values are logarithmized, and it is always non-negative. The input parameters of lognormal distributions are the mean and standard deviation values, alternatively the lognormal distribution can be defined by two percentiles. Figure 10 shows an example of two lognormal probability distributions with the same mean values but different uncertainty, i.e. different standard deviations (Std Dev).

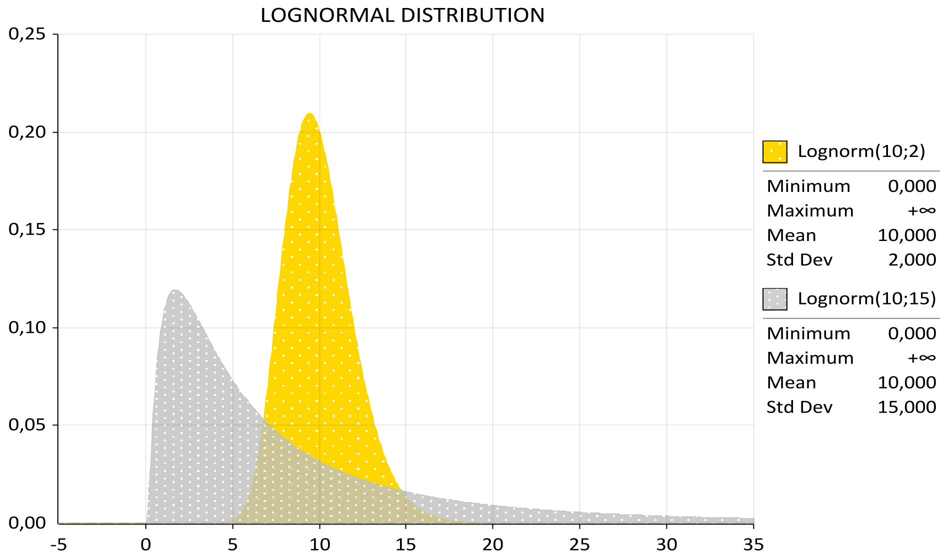

Figure 10 Lognormal probability distributions for two levels of uncertainty.

The Beta PERT distribution was chosen to represent uncertainties of estimated environmental and social scores. The input parameters for the Beta PERT distribution are the minimum, mode (most likely) and maximum estimates (Malcolm et al., 1959). The most likely value is given four times the weight compared to the minimum and maximum values, indicating that it is a more trusted estimate. This is particularly beneficial when dealing with expert and stakeholder estimations, since we usually are better at estimating most likely values than extreme values (Salling, 2011). However, the three input parameters (min, mode, max) means that the uncertainty about the most likely value is predetermined. To influence the uncertainty of the most likely value, the Beta distribution, which requires four input parameters, can be used instead. Figure 11 shows two Beta PERT distributions with different skewness and uncertainties.

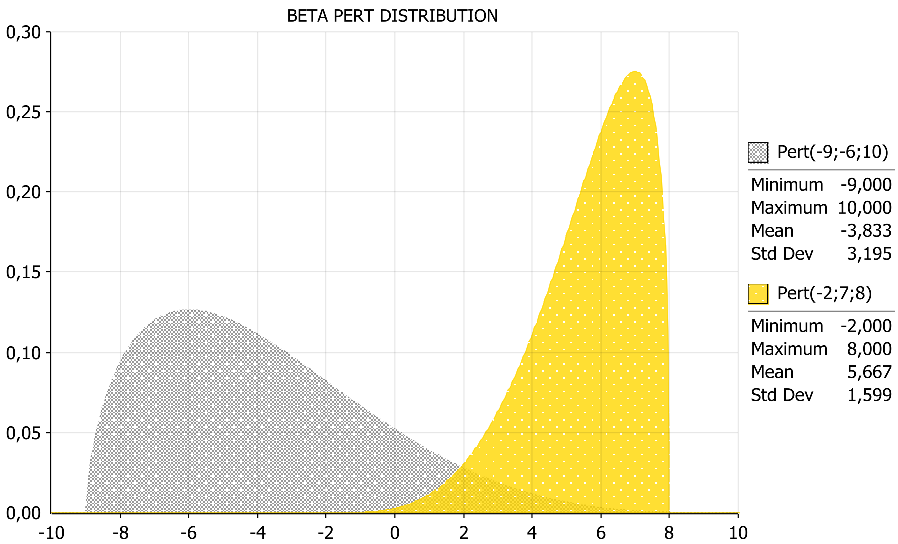

Figure 11 Beta PERT distributions with different skewness and levels of uncertainty.

To make use of the probability distributions, Monte Carlo simulations, further described in chapter 4.3, was selected as a quantitative risk analysis technique for the model. Monte Carlo simulations are used in calculations of net present values and sustainability indexes, as well as for sensitivity analyses.

5.2 Model application

A case study in the Göteborg region (Figure 12) was used to test, evaluate and illustrate the use of the proposed decision support model in a real-world situation. The Göteborg region consists of 13 municipalities and has about one million inhabitants. The municipalities are governing the water supply within their respective areas; however, four of the municipalities are fully or partly dependent on water produced in the city of Göteborg. There is currently 30 water treatment plants distributed throughout the region, of which 12 are fed with surface water, 15 with groundwater and 3 with artificial groundwater. The majority of the inhabitants receive drinking water produced of water from the river Göta älv. The river Göta älv has however a varying water quality and is considered to be particularly exposed to climate change, implying vulnerability in the region's water supply.

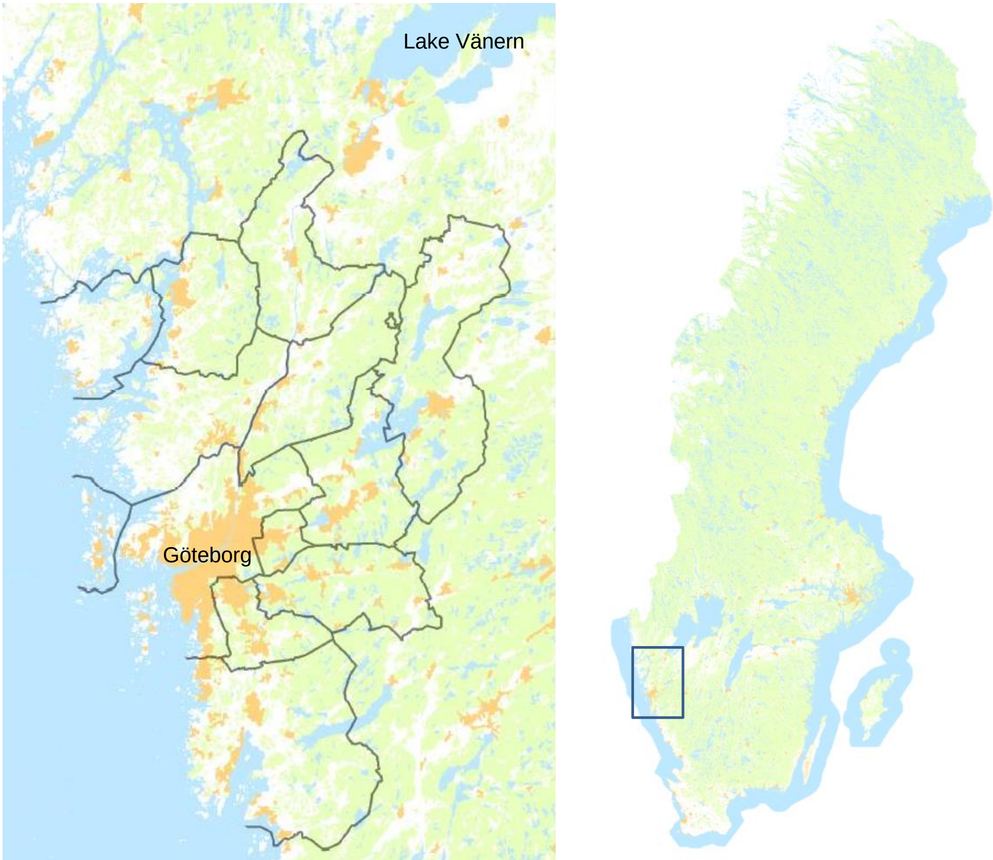

Figure 12 *The 13 municipalities of the Göteborg region (left) and their position in Sweden (right), © Lantmäteriet.*

Five alternative water supply interventions for the Göteborg region were evaluated in the case study. The alternatives were designed to meet regional sustainability goals and to illustrate decision situations regarding regionalization of drinking water utilities; (de)centralization of drinking water production; and source water quality and redundancy aspects. The alternatives were evaluated for two different time horizons, 30 and 70 years respectively, in relation to a reference alternative, which is a continuation of the present water supply system in the region. Costs and benefits were evaluated using two different discount rates, 1.4 % and 3.5 % respectively. The alternatives are described in Paper I and II, and summarized here:

- A1: Regionalized governance and centralized production from lake Vänern.
- A2: Regionalized governance and centralized production from the river Göta älv.
- A3: Regionalized governance and maintained semi decentralized production.
- A4: Maintained governance and decentralized groundwater dependent production.
- A5: Maintained governance, with additional source waters and treatment plants.

The prioritization, calculation, weighting and scoring of criteria for the Göteborg region was an iterative process performed parallel to the generic criteria development. The two stakeholder workshops used to develop the generic sets of sustainability criteria and economic costs and benefits were also used in the application of the model for the Göteborg region. The first workshop focused on prioritizing which costs and benefits to be monetized in the CBA, and the second workshop focused on weighting social and environmental criteria. The scoring of the criteria was later made in a process where different experts and stakeholders, as well as team members of this research study, were asked to assess minimum, maximum and most likely (mode) values of the criteria for the different alternatives in relation to the reference alternative.

The criteria weights and the min, mode and max scores for the social and environmental domains are presented in Table 7 and Table 8. *Health* and *Consumer's trust* were assigned the highest weights within the social sustainability domain, whereas *Water use,* and *Aquatic* and *Terrestrial ecosystems* were assigned the highest weights in the environmental domain.

All alternatives, except A3, were assumed to have a slightly positive effect on *Health.* The centralized treatment plants in A1 and A2 are of very high performance, decreasing the total risk in the region of having known or unknown hazardous substances passing the treatment plants. In A4, a large number of groundwater resources are used as source waters, and source water from Göta älv is replaced with increased extractions from the lakes Mjörn and Lygnern. The quality of the source water is higher, and the increased number of treatment plants means that presumed outbreaks will only affect a minor part of the population at a time. The same reasoning was applied to A5, in which access to an increased number of source water resources and treatment plants was assumed to provide a higher level of safety and an increased ability to quickly deliver drinking water from other resources and treatment plants if necessary. A3 was assumed to maintain the same level of safety as the reference alternative.

The three alternatives with regionalized governance, A1, A2 and A3, were assumed to have a positive effect on *Consumer's trust*, partly due to an increased possibility in larger organizations to employ and retain highly skilled personnel. The regionalized alternatives were also assumed to have a positive effect on *Water use,* due to higher initial maintenance and capacity increase of the distribution system in these alternatives and hence an assumed decrease in water leakage. The same alternatives, however, were assumed to have a negative effect on *Access and participation* due to a negative relationship between public access and the degree of organizational autonomy shown in previous research studies (Kurki et al., 2016; Lieberherr, 2011).

The assumed effects on *Aquatic ecosystems* were due to increases and decreases in number of water protection areas in the different alternatives. Water protection areas were assumed to have positive effects on the *Aquatic ecosystems* in their respective water resources. In addition to the water protection restrictions, e.g. regulating the handling of pesticides and petroleum products, source water resources also benefits from an increased environmental monitoring as well as protection in the legal processes of provisions of environmentally hazardous activities and water operations.

A1 was the only alternative assumed to have effects on *Terrestrial ecosystems, Materials for construction* and *Energy use at construction.* These were all were assumed to occur in connection with the source water tunnel construction. A4 was the only alternative assumed to have a positive effect on *Chemical use*, due to lower chemical use in treatment processes of groundwater in comparison with surface water.

Table 7 *Weights, min, mode, and max scores for the social domain.*

	Equity			Health			Consumer's trust			Access and participation		
Weights	0.23			0.36			0.3			0.11		
Scores	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max
A1	-1	0	1	1	4	5	2	4	6	-4	-3	0
A2	-1	0	1	-2	3	5	2	4	6	-4	-3	0
A3	-1	0	1	-1	0	2	1	3	5	-4	-3	0
A4	-1	0	1	1	3	4	-1	0	1	-1	0	1
A5	-1	0	1	1	3	4	-1	0	1	-1	0	1

Table 8 *Weights, min, mode, and max scores for the environmental domain.*

	Energy at construction			Energy at production and distribution			Water use			Materials for construction		
Weights	0.04			0.16			0.17			0.09		
Scores	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max
A1	-10	-7	5	-2	1	5	0	3	5	-7	-3	5
A2	-5	0	5	-2	2	5	0	3	5	-5	0	5
A3	-2	0	2	-1	0	1	0	2	4	-3	0	3
A4	-3	0	3	-2	-1	0	-1	0	1	-3	0	3
A5	-3	0	3	-2	-1	1	-1	0	1	-3	0	3
	Chemical use			**Non-recyclable waste**			**Aquatic ecosystems**			**Terrestrial ecosystems**		
Weights	0.12			0.08			0.17			0.17		
Scores	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max
A1	-3	-1	1	-3	0	3	-6	-4	-2	-5	-3	-1
A2	-3	-2	0	-3	0	3	-6	-4	-2	-2	0	2
A3	-1	0	1	-1	0	1	-1	0	1	-1	0	1
A4	2	3	5	-3	0	3	0	3	5	-3	-1	0
A5	-1	0	3	-3	0	3	0	1	3	-2	0	2

The economic costs and benefits prioritized to be included in the CBA for the Göteborg region are presented in Table 9. The methods used for monetizing the cost and benefit items are presented in detail in Paper II and are summarized here. The input data to the CBA for the different items and alternatives is presented in Sjöstrand et al. (2018).

Table 9 *Costs and benefit items to be monetized and included in the CBA for the Gothenburg region.*

Cost and benefit items	Description
Water utility items	Investments Operational and maintenance costs
Water supply reliability	Lost value added in economic sectors Losses for residential consumers
Water related health effects	Costs for healthcare Lost production Discomfort
Ecosystem services	Effects on hydroelectric production
Effects on agriculture due to water protection restrictions	Effects on agricultural production due to pesticide regulations

The three regionalized alternatives, A1, A2 and A3, were assumed to benefit from decreased operation and maintenance (O&M) costs due to economy of scale. A model to estimate changes in O&M costs was developed in Paper II. The O&M model provides a general relationship between number of connected consumers and O&M costs per cubic meter. To compensate the lack of data from large water utilities in Sweden, the model was based on a combination of water utility data from eight European countries, retrieved from the World Bank benchmarking database IBNET (2016), and Swedish water utility data, retrieved from the Swedish benchmarking database VASS (2015). There are of course several other parameters than number of connected consumers that also affect O&M costs. The purpose of the developed model, however, was to get a first estimate of the size of economic benefit from merging utilities. This estimate may then constitute the basis for decisions on further detailed analyses. However, the model may provide over-estimated benefits for regional utilities without centralized production systems, and hence benefit A3 over others in the analysis. The reason for this is that the water utilities that the O&M model is built on are likely to have somewhat fewer treatment facilities than A3 for the same number of connected consumers.

All alternatives, except A3, were assumed to benefit from a decreased risk of water delivery failure. A3 was assumed to maintain the same risk level as the reference alternative. The economic valuation of water supply reliability was based on assessments of economic losses in different economic sectors due to water supply disruptions, combined with assessments of residential consumers' willingness to pay to avoid water supply disruptions (ATC, 1991; Brozović et al., 2007; FEMA, 2011). This resulted in a total cost for both economic sectors and residential users of 639 SEK per capita and day.

All alternatives, except A3, were also assumed to benefit from a decreased risk of negative health effects. Again, A3 was assumed to maintain the same risk level as the reference alternative. The economic cost of water related infections was valued as the sum of healthcare costs, costs of lost production and costs of dis-utility (Hurley et al., 2005), resulting in a total cost of about 14,305 SEK per case (mean value).

The economic consequences for farmers from not receiving permits for pesticide use for certain crops were estimated based on assessments of yield difference from conventional and organic production due to increased/decreased water protection land area in the different alternatives. Effects on hydropower production in the river Göta älv over the time horizons was valued based on spot prices and estimated prices by the SKM Long Term Power Outlook (Nord Pool, 2016; SKM, 2016). Water utility costs associated with implementing the alternatives, such as costs for new treatment plants, pipelines, pumping stations, water protection areas, tunnel constructions etc., were estimated based on information gathered from experts at water utilities, and past and ongoing Swedish projects.

Results from the economic analysis are presented in Paper II. The choice of discount rate and time horizon had a significant impact on *NPV* outcome, see Figure 13 and Figure 14, indicating that 30 years was a too short time horizon to appropriately account for the long-term benefits. A4 and A5 leveled out around year 50, whereas the other alternatives continued to increase in *NPV*, though with a significantly lower rate for A1 and A2. The sudden drop in *NPV* increase of A1, A2, A4 and A5 around year 40 is due to some major investments in capacity and treatment assumed to take place in the reference and A3 alternatives, and to some extent also in A4 and A5, by that time.

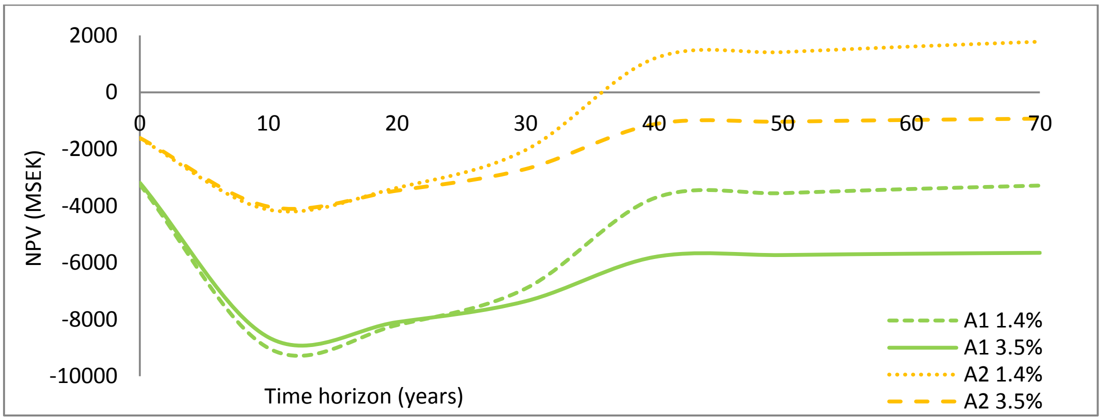

Figure 13 Mean net present values (NPV) in million SEK for A1 and A2 over the next 70 years.

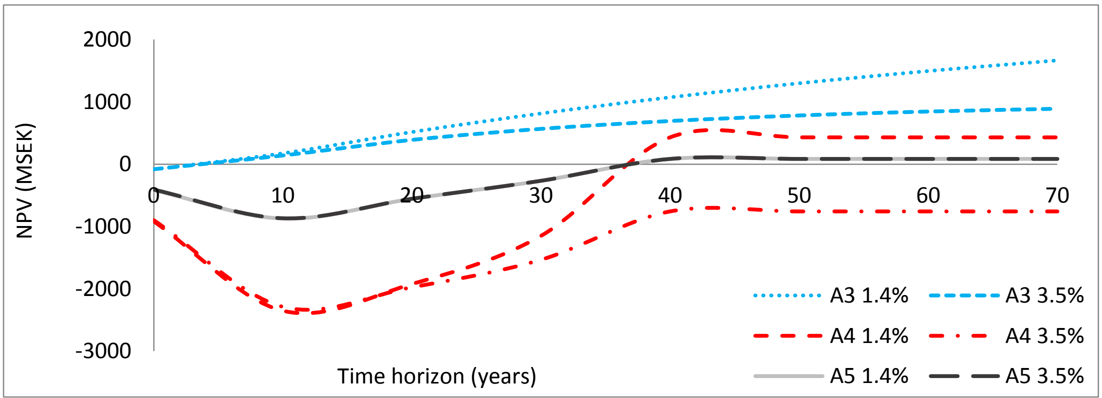

Figure 14 Mean net present values (NPV) in million SEK for A3, A4 and A5 over the next 70 years.

Results from the social, environmental and economic analyses are presented in Paper I and summarized in Figure 15. All alternatives are expected to contribute to a slightly improved social sustainability, whereas the results are more varying in the economic and environmental domains.

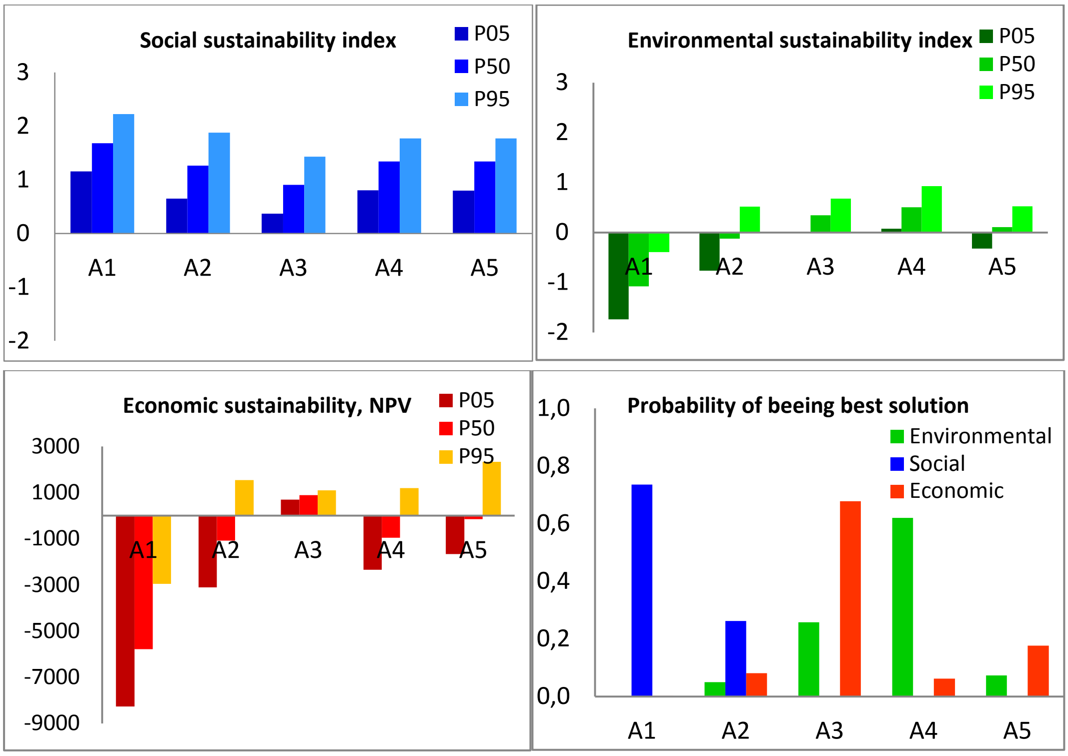

Figure 15 *Social, environmental and economic analyses of the five interventions evaluated for the Göteborg region. The economic domain was here analyzed for a 3.5 % discount rate over a 70 year time horizon.*

The overall sustainability index indicates that A1 is the least sustainable solution (Figure 16). A3 has the highest probability of being the best overall sustainability alternative, if applying equal weights between the sustainability domains.

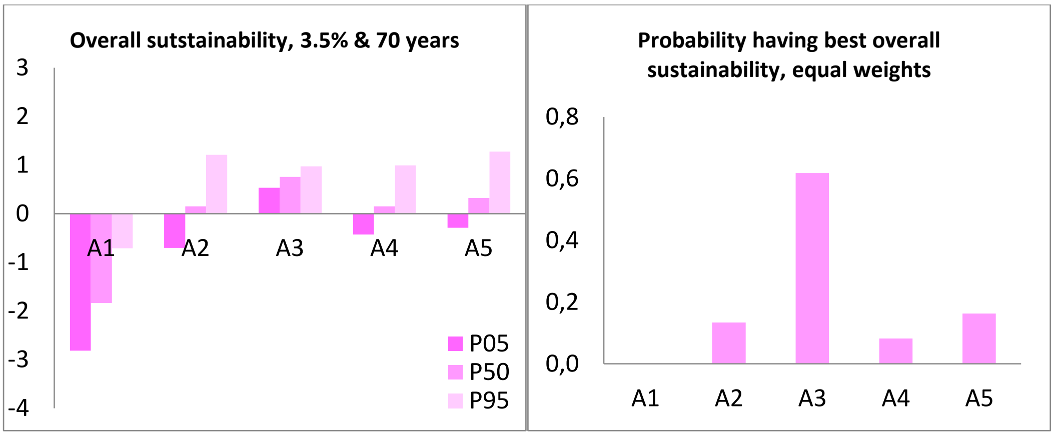

Figure 16 *Overall sustainability index for the five alternatives (left) and probability of being best overall sustainability solution (right) for 3.5 % discount rate and a 70 year time horizon. The sustainability domains have here equal weights.*

Examples of sensitivity analyses of the alternatives are shown in Figure 17 to Figure 21. The analyses are based on the Monte Carlo simulations and show the contribution of input parameters from both environmental and social criteria and economic costs and benefits on outcome uncertainty. As some economic input parameters for the assessed alternatives were estimated separately from the reference alternative, e.g. risk estimates of *delivery failures*, those parameters are presented separately in the figures and hence not as the difference between them. For this reason, the risk of *delivery failure* seems to contribute more to outcome uncertainty than it actually does. Along with some economic investment parameters, which contributed highly to outcome uncertainty, the social criteria *Health* and *Consumer's trust* were also on top of the lists in many alternatives.

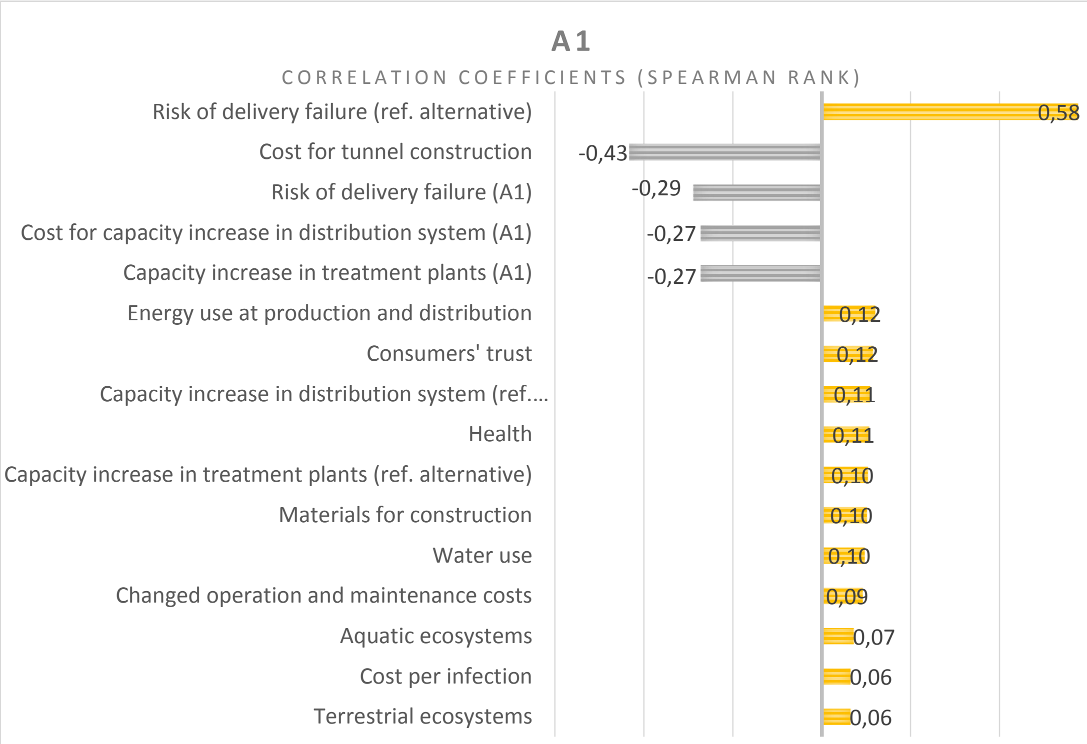

Figure 17 *Sensitivity analysis of A1.*

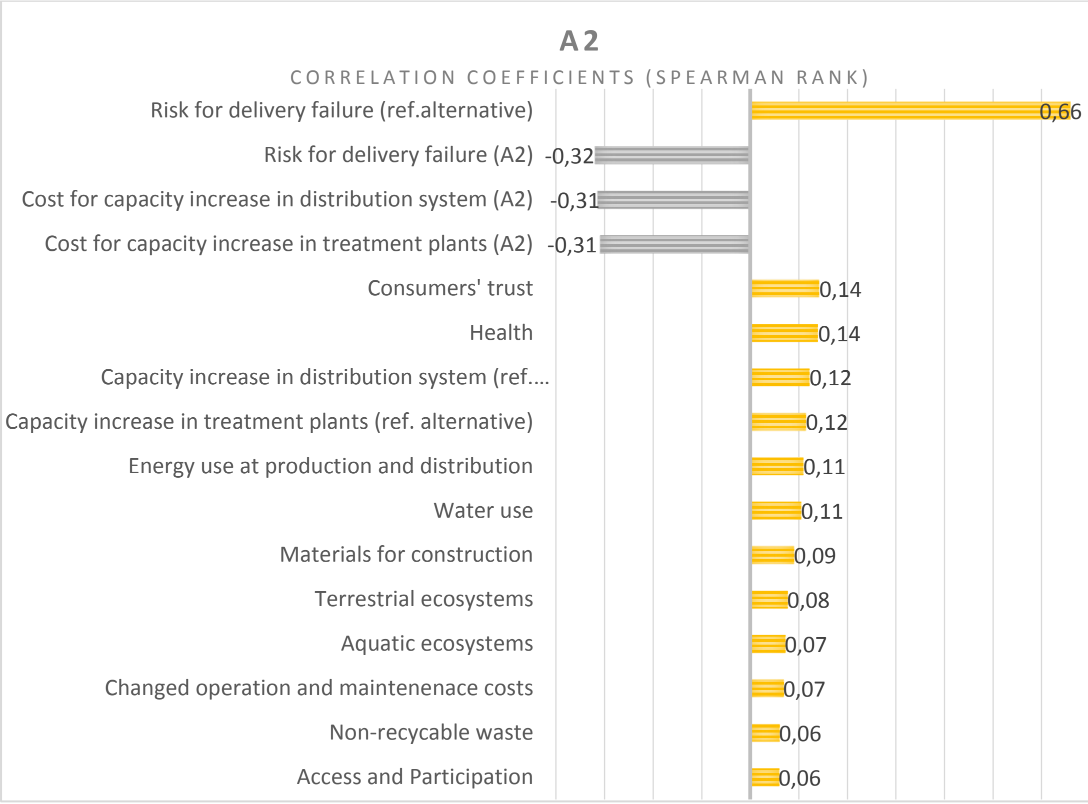

Figure 18 *Sensitivity analysis of A2.*

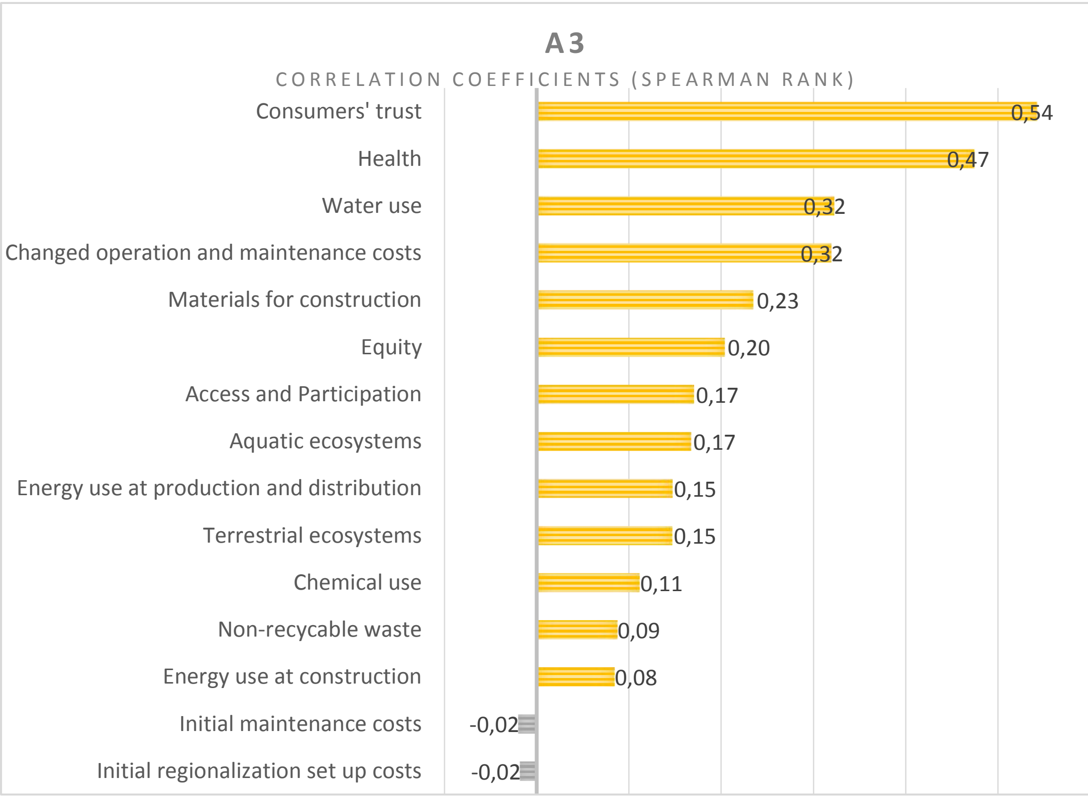

Figure 19 *Sensitivity analysis of A3.*

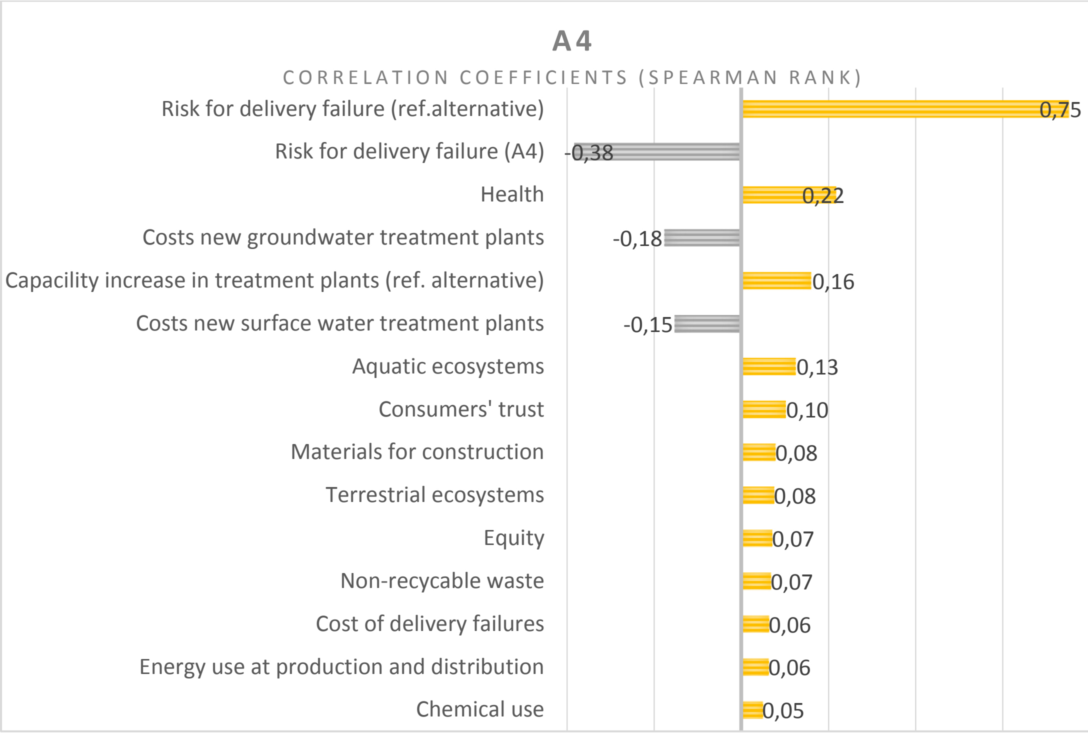

Figure 20 *Sensitivity analysis of A4.*

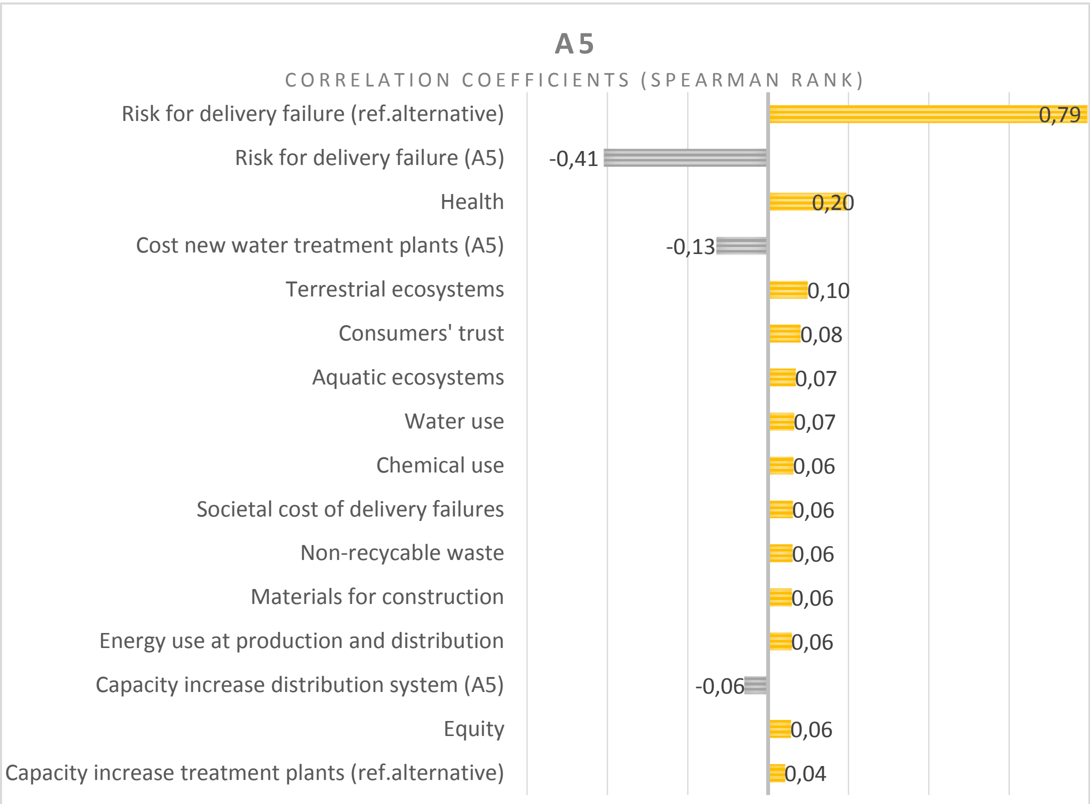

Figure 21 *Sensitivity analysis of A5.*

6 DISCUSSION

The main purpose of this thesis was to develop and apply a decision support model for sustainability assessment of regional water supply interventions. This chapter provides a discussion of the contents of this thesis work, including limitations and applicability of the developed model and the fulfilment of the overall aim and the specific objectives.

6.1 Requirements in sustainability assessment methods

In the process of developing a model for sustainability assessment of regional water supply interventions, national and international research literature was searched for requests in suitable methods. The way to achieve a sustainable water sector differs between countries and jurisdiction (Rathnayaka et al., 2016). But there are still some shared requests on a sustainability assessment method, and the proposed decision support model was developed to meet several of them. According to Brattebø et al. (2013) for example, a sustainability assessment method needs to be transparent, valid and holistic. Transparent decision-making is facilitated by the model by using the structured methods cost-benefit and multi-criteria decision analyses as a basis for the evaluations. Further, the model includes a comprehensive set of generic sustainability criteria, co-developed with a broad stakeholder group. This allows for assessments of alternatives within each of the economic, social and environmental sustainability domains as well as of an overall sustainability. This enables coherent and thorough decisions.

A sustainability assessment method also needs to be inclusive and allow for public and stakeholder participation, which is acknowledged to improve the quality and implementation of governance (UNECE, 1998). Public and stakeholder involvement also provides for viable decisions and facilitates investments such as large infrastructure renewals (Palaniappan et al., 2007). The use of MCDA as a basis for the model facilitates consideration of stakeholder and public preferences. In the case study application, stakeholder and public participation was demonstrated by representatives taking part in prioritizing and weighting the criteria as well as in the scoring and economic valuation processes, as specialists within their respective areas of expertise.

Due to long asset and infrastructure life times, and due to the very concept of sustainability, the ability to consider long time horizons as well as uncertainties and trade-offs in future context conditions is also an important feature in a sustainability assessment method (Störmer et al., 2009). All of the above requests laid the foundation for the set of requirements defined for the model. They were hence a reason for choosing CBA and MCDA as basis for the model, as well as for choosing a probabilistic approach to allow for consideration of both present and future uncertainties.

6.2 Cost-benefit analysis and economic valuation techniques

Cost-benefit analysis has been used for sustainability assessments in a number of studies. CBA is both praised and criticized as a decision support tool. It is for example considered attractive for guiding public polices as it embraces gains and losses for all individuals in the society for which the analysis is carried out; it uses a familiar measurement scale (money) to display the effects on society; and the economic valuations are based on people's actual preferences (DCLG, 2009). CBA is however criticized for the same reason it is appreciated, i.e. for allowing individuals' preferences to be the main decisive factor in informing public decisions (Pearce et al., 2006). It is also criticized for relying too much on Kaldor-Hicks compensation, meaning that those that are made better off by the analyzed intervention could hypothetically compensate those that are made worse off. Performing a distributional analysis is hence an important part of a CBA for highlighting and understanding how the costs and benefits affect different stakeholder groups in the short and long run. Distributional analysis was however not demonstrated in the case study application in this thesis.

One of the main efforts in CBA lies in applying suitable economic valuation techniques to quantify identified costs and benefits into monetary terms. Monetization of costs and benefits not related to existing markets is difficult. There are a number of different valuation techniques to choose from, but it is far from always certain which technique is most suitable to apply in a real-world problem (Munda, 1995). In order to facilitate the application of the proposed decision support model, Paper II shows how some key costs and benefits can be monetized and integrated in a CBA. Economic valuation methods to assess effects on water supply reliability and water safety were presented and applied, and a model was developed to estimate changes in operation and maintenance costs when small local utilities are merged into larger regional ones.

It is, however, almost never possible or economically defensible to monetize all costs and benefits that may arise as a result of a proposed alternative (DCLG, 2009). Hence, a prioritization is needed regarding which effects are reasonable and possible to assess, and with which degree of certainty. This can be particularly important at an overarching regional level. In the application of the model, identification and prioritization of costs and benefits were done by use of stakeholder workshops, enabling viable and accepted decisions.

6.3 Multi-criteria decision analysis

Several studies have proposed MCDA for evaluating sustainability of water supply interventions (Lai et al., 2008; Rathnayaka et al., 2016; Scholten et al., 2015). MCDA meets several of the above-mentioned requirements on sustainability assessment methods. It can be used to assess both weak and strong sustainability depending on choice of compensatory or non-compensatory techniques (Hopwood et al., 2005; Rosén et al., 2015). It provides a means for structured and transparent evaluations of alternatives and it places a large emphasis on the judgements of involved stakeholders. MCDA can also account for conflictual and uncertain effects of decisions. The main advantage of MCDA is that it makes it possible to consider a large number of data, relations and objectives, so that the decision problem can be studied from multiple angles (Munda, 1995). The proposed decision support model makes use of a compensatory MCDA technique, i.e. the linear additive technique, allowing for trade-offs between sustainability criteria and between sustainability domains. The linear additive technique is applied both within the social and environmental domains, calculating domain specific sustainability indexes, and between the three sustainability domains, calculating an overall sustainability index. Most public decisions allow for trade-offs (DCLG, 2009). However, when trade-offs cannot be accepted, e.g. when ethical issues are crucial for the decision, the model can still be used to identify whether compensation occurs in an alternative or not.

There is however critique of MCDA as well. One critique concerns the fact that preferences are normally elicited from a relatively small group of decision-makers and stakeholders, and not, as in CBA, aggregated preferences of all individuals in the society. It is therefore important that the decision support model is implemented so that the relevant groups in society are included and represented as widely as possible, and that the assessments are not only based on expert elicitations. Another critique concerns the fact that there is no collectively used method for incorporating time dependency and long term consequences for MCDA criteria (DCLG, 2009; Montibeller & Franco, 2011). In Paper I, time-differentiated environmental and social effects are incorporated in the analysis by letting the minimum, most likely and maximum scores be representative values for the entire time period and the uncertainties surrounding this overall assessment.

6.4 Applicability of proposed model

The application of the proposed model demonstrates its possibilities to aid in regional decision-making. The use of MCDA as a basis for the decision support model enables analyses and comparisons of multiple criteria. It allows for analysis of performance within each sustainability domain and for each specific criterion.

The model also facilitates analysis of uncertainties associated with each alternative in a systematic and transparent way.

By combining MCDA with CBA, valuations based on welfare economics of private costs and benefits as well as externalities can be included in the sustainability assessments, and the possibility arises to assess economic profitability in addition to sustainability. The combination of CBA and MCDA offers a scientifically sound decision framework for supporting decisions where stakeholder judgement is of crucial concern and criteria such as equity and final environmental values cannot be easily condensed into monetary terms.

The proposed model provides increased visibility of economic costs and benefits, as well as of societal and environmental aspects, to enhance the analysis of regional water supply interventions. The decision support model hence facilitates selection of a preferred course of action. However, the assessment result does not by default give the final decision. The principal aim with the model is to construct a liable help for decision-makers that reflects his or her preferences and considerations as well as those of affected societal groups. The model is thus meant to guide, inform and support rather than replace managerial judgement. Ethical and political discussions and negotiations are still needed to guarantee a just evaluation of values and preferences. Human judgement is hence vital in making a final decision (Ashley et al., 2004; Aven, 2012).

Uncertainties about estimated cost and benefit values and social and environmental scores are represented by probability distributions and handled by means of Monte Carlo simulations. The use of Monte Carlo simulations enables an easy and controlled extraction of information from the probability distributions. The result from a Monte Carlo simulation is a distribution of possible outcomes, which can be compared with performing thousands *What-if* analyses. User friendly Excel add-in software, like @Risk and Crystal Ball, can be used to perform both the simulations and sensitivity analyses.

Some experiences and identified difficulties from the case study are worth mentioning here. The case study application of the model accentuated the significance of a scoring aid. It is important that the scoring is consistent, both regarding the actual performance level of an alternative on a specific criteria, and regarding present and future uncertainties surrounding this performance. This is particularly important if different people are responsible for different parts of the scoring. Hence, the present scoring aid will be further developed and complemented with example scenarios provided with associated suggested scores.

The case study also displayed some difficulties within the economic domain, for example in finding valid data for identified costs and benefits. In addition, several of the economic valuation techniques applied in Paper II were not originally developed for Swedish conditions. In order to facilitate the economic analyses, future studies will be focused on identifying standard values and simplified economic valuation techniques.

It is also important to remember that the economic as well as environmental and social assessments should be made with consideration of potential future changes, i.e. how for example climate change will affect the performance of an alternative on a specific criterion in the future. Further, different potential futures, reflecting e.g. different climate change or supply and demand developments, can be analyzed by varying assessment scenarios.

6.5 Water supply sustainability

Sustainable governance in the water sector is crucial for protecting the social and public goods aspects of water and for ensuring the society a safe and reliable water supply. Water supply governance, however, is performed in a variety of ways and is often judged as inflexible and suffering from short-term politically motivated decision-making, deficient in addressing long term uncertainties, stakeholder involvement and alternative strategies (Beh et al., 2011; Economides, 2012; Ferguson et al., 2013; Scholten et al., 2015; Störmer et al., 2009). Environmental, social and economic drivers are now making it more attractive to manage the water services at larger, regional scales, and consequently some of the above issues, common in local governments, may be overcome. However, inter-municipal cooperation is not beneficial for all municipalities (Thomasson, 2018), and alternatives must be assessed and compared from case to case to find the most feasible solution for each specific region (Kurki et al., 2016). Yet, decisions regarding drinking water cooperations and other regional interventions are often made without a proper method of balancing the economic, health and environmental effects thereof (McFarlane, 2003). And as a result, the decision-makers do not use all necessary information in choosing between identified management alternatives.

In the case study application of the proposed decision support model, five alternative interventions were evaluated for the Göteborg region. Two alternatives with a completely centralized drinking water production were the least economically and environmentally beneficial alternatives, whereas the same alternatives were the most socially sustainable for the region. The three alternatives with a regional, inter-municipal, organization were, among other things, assumed to benefit from economy of scale and improved consumer’s trust. These advantages were most clearly distinguished in the alternative with a regionalized organization but maintained semi-decentralized production (A3), since the economic gains were not reduced by major investment costs in this alternative. The two alternatives with increased number of source waters and water treatment plants, A4 and A5, were, along with the centralized alternatives A1 and A2, assumed to benefit economically from decreased risks of delivery failure and negative health effects. A4 and A5 did however not experience the same large investment costs as the centralized alternatives, and were thus more economically beneficial. For the Göteborg region, the case study hence indicates that forming a regional water supply organization and/or increasing the redundancy in the system by utilizing more water resources, might be a sustainable way forward.

The application of the proposed model demonstrates its possibilities as decision support for comparisons of alternative interventions. The model can help decision-makers in balancing the economic, social and environmental effects of alternative interventions. It allows for aggregation of gains and losses across the sustainability domains after which the overall sustainability, as well as the specific sustainability criteria and domains, can be compared and evaluated. The decision support model hence facilitates well-informed and viable decisions, a basis to ensure the society a safe and reliable water supply for generations to come.

7 CONCLUSIONS

This chapter summarizes the main conclusions of the thesis and presents possible further studies and new applications of the decision support model. Conclusions that are more specific to the developed model and its applications can be found in the attached papers.

The main conclusions of this thesis are:

- A regionalization of the water sector is encouraged in several countries as a means to tackle present and future challenges.
- Few studies have focused on assessing the sustainability of the formations of inter-municipal cooperations or other large scale, inter-municipal policies and interventions that regional decision-makers are faced with.
- A novel sustainability decision support model, which is able to combine fully monetized costs and benefits with criteria in the social and environmental sustainability domains, is provided in the thesis.
- Key sustainability criteria, specifically developed to deal with inter-municipal, regional water supply interventions, are identified, presented and applied. The economic sustainability criterion is assessed by means of CBA based on impacts on human well-being. The social and environmental criteria are assessed by means of MCDA based on impacts on moral principles such as equity and final values of the environment.
- By combining MCDA with CBA, valuations based on welfare economics can be included in the sustainability assessments, and the economic profitability of alternative regional interventions can be assessed in addition to sustainability. As many municipal decisions are based on economy, the possibility to separately examine alternatives' economic effects on society is valuable for the political reviews and deliberations of the assessment results.
- The probabilistic methodology allows for a structured and transparent uncertainty analysis of quantified values. This enables calculations of probabilities that alternatives e.g. exceed environmental threshold values; are economically profitable; or, perform best with respect to one or several of the sustainability domains. This also facilitates communication between the municipalities as well as with the residential consumers and stakeholders.
- The decision support model allows for weighting the economic, social and environmental domains differently, depending on the decision-makers preferences regarding sustainability.

- The practical case study application provides information on how regionalization, centralization and other strategic water supply decisions might affect the society, environment and economy.
- The results of the thesis contribute to the decision support toolbox municipalities and water providers need to make proper evaluations and informed decisions for a long term sustainable water supply.

The decision support model offers possibilities for further development and additional applications. The following areas for further research have been identified:

- Apply the model to regions with other geological, demographical, and water availability conditions than the Göteborg region in order to improve and further evaluate its applicability. This research area is currently being explored as the model is tested and adjusted for water supply decision-making at the island Gotland on the Swedish east coast, where water scarcity, sparsely populated areas and widely differing geological conditions provide new challenges.
- By applying the model in regions with other conditions, the research would not only benefit the model itself, but would be an opportunity to compare the importance of different sustainability criteria depending on certain pre-conditions, and could hence improve the ethical and political reviews and deliberations regarding alternative scenarios in those areas.
- Further compare the suggested decision support model with other sustainability assessment methods.
- This thesis, and proposed decision support model, does not include the identification and design of possible alternatives. That is an important part of the overall decision-making process for achieving a sustainable water supply, and is hence a possible future research area for model improvement.
- Further develop the scoring aid, which will be complemented with example scenarios provided with associated suggested scores.
- Several of the economic valuation techniques applied in Paper II were not originally developed for Swedish conditions. The model would hence benefit from research on such valuation techniques with a focus on Sweden, as the resulting effects of different cost and benefit items may depend on national legislation or other country-specific conditions. For example, the economic value of water supply reliability would be interesting to develop further for Swedish consumers and economic sectors. The same applies for the

developed O&M model, in which there are uncertainties regarding comparability between countries and the limited data availability.

- Uncertainties about costs, benefits and other sustainability criteria are handled by uncertainty distributions and integrated in a clear and transparent way. However, the handling of uncertainties about future conditions, such as climate change, population growth and regulatory restrictions, have not been discussed thoroughly, and could hence be a possible future research task.

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