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Capacity expansion modelling to aid water supply investment decisions

A thesis submitted to the University of London for the degree of Doctor of Philosophy

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Declaration

I, Silvia Padula, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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I would like to thank my supervisor Julien Harou for supporting my ideas and providing me the opportunity to carry on this research. His skills and expertise has contributed greatly to my learning and success in completing this thesis. I would also like to thank my second supervisor Lazaros Papageorgiou for his support and motivating discussions throughout my PhD studies.

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ADDITIONAL CONTRIBUTIONS

The EBSD model formulation presented in Chapter 2 is the result of a collaboration between the author and a group of engineers at Halcrow including Fida Choudhury, Yiming Ji and Mohammad Ahmad. The author developed the model's mathematical formulation and produced results presented in Chapter 2, while the Halcrow group was in charge of providing the input data.

Dr. William Baker, an expert in water regulatory economics at NERA Economic Consulting, provided advice regarding the model formulation implemented in Chapter 5.

Section 3.7.1 is the result of a work conducted in collaboration with Dr. Tohid Erfani. Dr. Tohid Erfani contributed Figure 29.

Appendix II is the result of work conducted in collaboration with a former MSc student Derek Marchant. The author provided the model and the input data while Derek Marchant ran the model and made the plots presented in Appendix II. The introduction and sections II.3, II.4, II.5, and II.6 were originally written by Derek with some revisions by the thesis author and supervisor Julien Harou.

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ABSTRACT

Increasing population, economic development, and environmental changes imply that maintaining the water supply-demand balance will remain a top priority. Water resource systems may need to be expanded in order to respond to demand growth. Capacity expansion studies can be used to answer the question of what the optimal expansion size, timing and location of new infrastructure should be. This thesis develops and applies capacity expansion optimisation modelling approaches. We begin with the 'Economics of Balancing Supply and Demand' (EBSD) planning framework used by the water industry since 2002 in England. The base model is formulated as a mixed integer linear programming optimisation model that selects the least cost annual schedule of supply and demand management options that meet forecasted demand over the planning horizon. Custom water saving profiles are allowed for demand management options. Multiple demand scenarios are considered to ensure the supply-demand balance is preserved under different demand conditions and that operating costs of selected options are accurately assessed. The base deterministic EBSD model is applied to the water companies of South East England (the WRSE area). Various extensions to the EBSD framework are then proposed and implemented. The model formulation is first expanded to incorporate a generic cost estimate for options not yet proposed in water company resources management plans. This allows to extend the WRSE network with new inter-company transfers for which costs are represented by a concave cost curve approximated by a piece-wise linear function. Considering additional interconnections allows evaluating the financial implications of further interconnectivity in the WRSE area. Next, an extension is proposed to improve the application of the stochastic version of the EBSD approach. The proposed method allows to identify the set of future capacity expansions that withstand uncertainty of supply and demand estimates and still achieve a required reliability. The method consists of an iterative process: at each iteration the EBSD optimisation model is run and the reliability of the solution set (supply-demand schedules) is tested under Monte Carlo simulation. Ad-hoc model constraints are introduced at each iteration to enable the EBSD model to exclude unreliable solutions identified at previous iterations. Next, the English price-cap regulatory process is represented within a modified EBSD model formulation. The model identifies future capacity expansions that maximise water company profit under constraints on the maximum price that can be charged to customers and on the allowed rate of return. The incentive schemes that the regulator uses to reward (or penalise)

companies for out- (or under-) performance, are also represented. The goal is to help explain how the current regulatory system of incentives motivates water company investment decisions. Two further extensions are then presented in the appendixes. The first one allows the EBSD model formulation to be extended so that costs of activated schemes are accounted over the schemes' useful life, beyond the typical 25-30 year planning horizon. This eliminates biased comparisons of schemes with different economic lifetimes. With the second extension, a diverse set of supply-demand schedules are generated, that solve the capacity expansion problem and are sufficiently 'close' (in terms of costs) to the least-cost solution. Generating multiple near-optimal solutions gives an idea of what alternative plans are available in addition to the least-cost one. This allows the consideration other un-modelled factors or strategic priorities in the decision making process.

Chapter 1

INTRODUCTION

1 Background

Increasing demand for water, higher exploitation of resources, and excessive water pollution due to agricultural and industrial expansions have caused a social and political alarm (Mohammad Karamouz et al., 2003). Water is not always fairly distributed: there is often '*too much or too little or what exists is too polluted or too expensive*' (Daniel P. Loucks et al., 1981). In addition to this, global change drivers such as climate change, population growth and land use changes will create new challenges in the near future. In areas where pressures on water supplies are high, maintaining the supply-demand balance at an economically and ecologically sustainable level is the priority for all decision-makers involved in the water resources planning process. Planning for sustainable development of water resources may include new supplies, but also strategic actions such as water conservation measures, leakage reduction, reduced water abstraction within the limits of the system. Water resource systems may need to be expanded to take account of the growing demand for resources and services. Capacity expansion studies are undertaken when existing facilities for withdrawing, storing and transferring water between different users become insufficient or cannot meet the existing or projected demands. Since the 1950s capacity expansion models have been used for various public services where substantial capital investments are needed such as heavy process industries, communication networks, electrical power services, schools and roads and water resource systems (Luss, 1982). Given the time it takes to plan, fund and build new infrastructure capacity expansion planning is of vital importance for answering the question of what the optimal expansion size, timing and location of new production facilities should be.

This thesis aims to assess and address some key issues related to the capacity expansion problem applied to the English water supply industry. The starting point is the 'Economics of Balancing Supply and Demand' (EBSD) planning approach used by the water industry in England since 2002. The thesis is structured with an introduction followed by five technical Chapters, a conclusion Chapter and two appendices. The introduction sets the context, introduces and justifies the methodology used, outlines the research problem and thesis objectives and summarises the scholarly contributions of the technical Chapters. The literature review is split between the introduction, where the main modelling approaches for water resources planning are introduced, and each technical Chapter where the specific literature relevant to each contribution is reviewed. The thesis finishes with a conclusion summarising what has been learned and gained by this work, and provides directions of future inquiry.

1.1 Water resources systems and their planning

Water resources systems consists of two different environments: a physical, chemical and biological environment which includes interrelated water bodies and structures (each element may impact on the performance of other system's components), and a cultural environment which includes our political, economic and social interrelation with the environmental system (White I.D., 1992). The two environments are inseparable.

Water resources systems analysis is the activity of managing and planning water resource systems and frequently consists of four main consecutive steps: a. problem definition and data collection; b. modelling; c. decision making; d. implementation of the project (Mohammad Karamouz et al., 2003) as shown in Figure 1.

Models are a simplified representation of the system and commonly consist of breaking down the complexity of the system into its main component parts. (Daniel P. Loucks et al., 1981) refers to modelling as a tool that allows abstracting from the real word the components that are important for the decision making process. Modelling approaches can be broadly classified into the following categories: deterministic versus stochastic, optimisation versus simulation. Their detailed description is introduced in paragraph 1.3 of this Chapter.

In the following phase stakeholders and decision-makers analyse the model solution ((in deterministic simulation or single objective optimisation) or set of alternative solutions (with stochastic simulation or multi-criteria optimisation). In optimisation methods, alternative solutions can be generated through an approach called 'modelling to generate alternatives' (also applied in this thesis, see Appendix II). Decision makers and stakeholders typically evaluate one or a set of alternatives and select one based on their preferences. The last phase of the planning process consists on the construction or implementation of the selected strategy. The work conducted in this thesis falls within the ‘modelling' phase highlighted in the dashed red box of Figure 1, although the decision-making phase is also relevant.

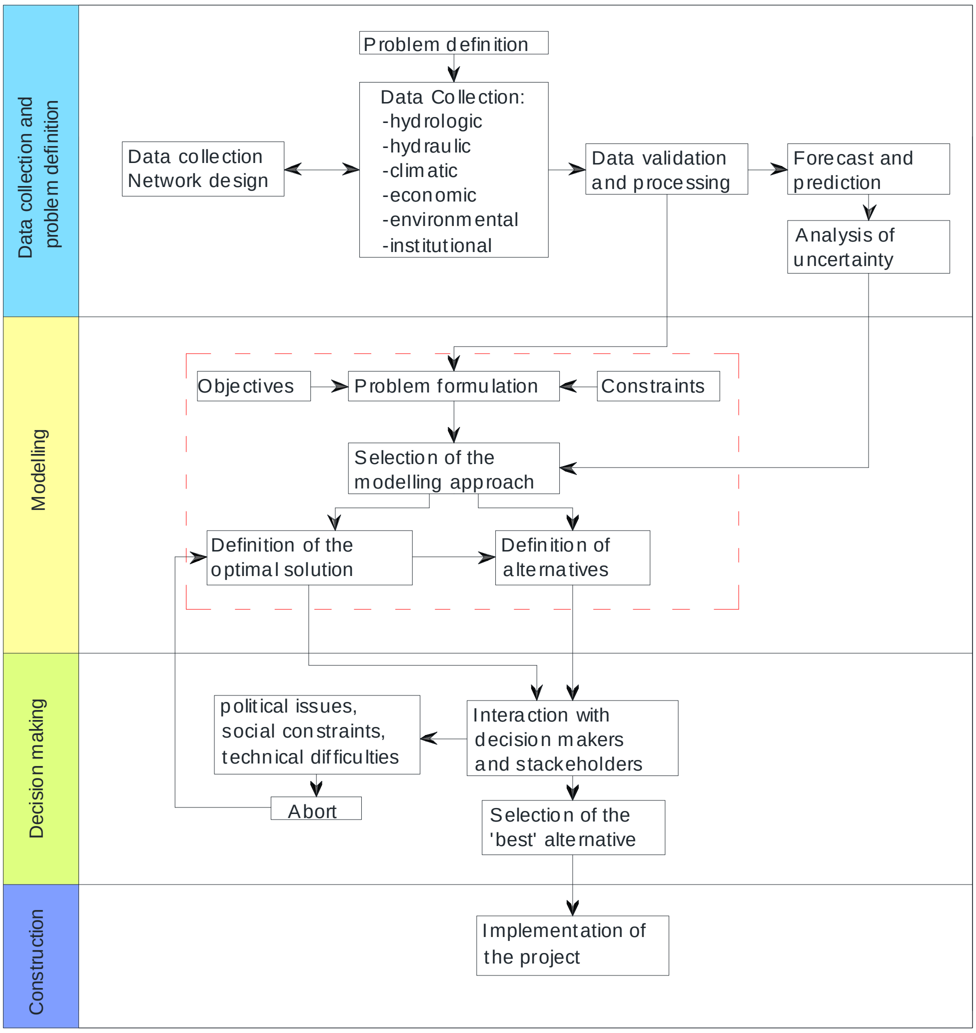

Figure 1: The water resources planning process, adapted from (Mohammad Karamouz et al., 2003)

1.2 Capacity Expansion problems

Choosing an appropriate schedule of infrastructure upgrades and investments is a classic water resource systems analysis problem (Olaoghaire and Himmelblau, 1974, Loucks et al., 1981, Mays, 2005, Loucks, 2006). Capacity expansion planning consists of determining future expansion in time, size and locations of the existing assets as the demand of a specific commodity increases. A classical objective function minimises the net present value of the total cost of the expansion (see section 1.3 for net present values evaluation). Decision makers often impose constraints to the problem, these can be budgetary limits or upper bounds on expansion sizes, excess capacity and capacity shortages (Luss, 1982). Expansion polices are considered over time for a planning horizon (typically 20 to 100 years for civil infrastructure). Some capacity expansion problems allow for capacity shortage at certain shortage costs. This means that the demand can remain temporarily unsatisfied or temporarily satisfied by renting the commodity from an external source.

One of the earliest work on capacity expansion problems is from Manne (1961). The simplest application of the problem considers a deterministic demand that grows linearly over time at a constant yearly rate of X/t'where X is the expansion size at time t' (see Figure 2). If we suppose that whenever demand reaches the existing capacity (see for example point A in Figure 2) 'X' units of new capacity are installed, and that the installed capacity has an infinite economic life, then the course of demand over capacity can be plotted over time as in Figure 2. In Figure 2 terms X_0, X_1, X_2 and X_3 represent the expanded capacity at time steps t_0, t_1, t_2 and t_3 respectively.

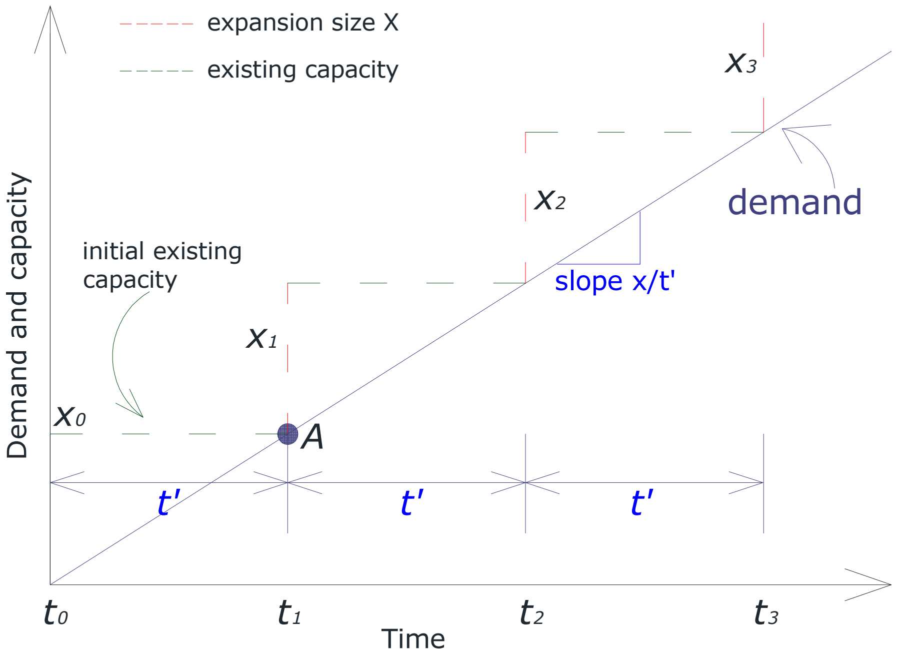

Figure 2: Optimal capacity expansion problem (adopted from Manne, 1961).

By plotting the evolution of the excess capacity X over time, we obtain Figure 3.

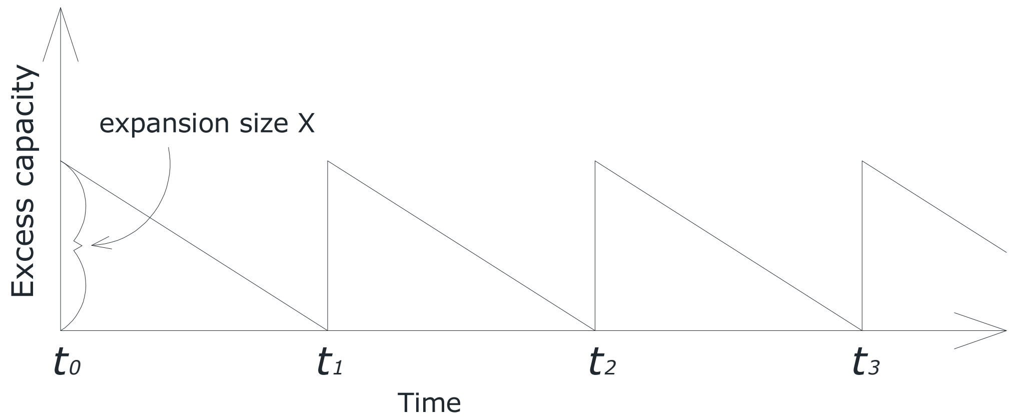

Figure 3: Excess of capacity over time (adopted from Manne, 1961).

Each time any capacity X is added there are fixed costs (setup costs required to initiate an activity) and variable costs (related to the level of the activity) occurring. The cost function of a capacity expansion problems therefore typically exhibits fixed costs and substantial economies of scale (the average cost per unit of capacity decreases with the expansion size) as shown in Figure 4.

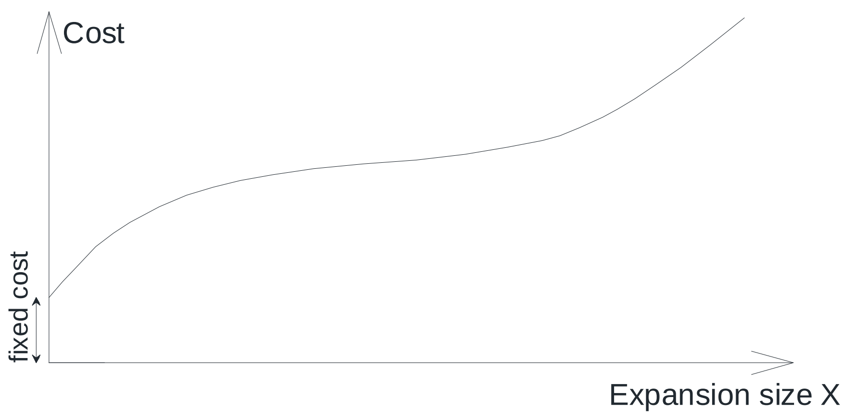

Figure 4: Typical cost function (includes fixed and variable costs) for additional capacity, adapted from (Daniel P. Loucks et al., 1981)

The installation costs that results from a capacity increment of size X can be typically represented by a power function $C(X)=kX^{\alpha}$ where k is a positive constant, while α is the economy of scale factor defined between zero and one. Typical values of α for water and waste water treatment facilities change between 0.6 and 0.8 (Daniel P. Loucks et al., 1981). α is equal to 0.35 for canals and storage dams which have high economies of scale and can be closer to 1 for large systems such as municipal waste-water treatment plants (Revelle, 1999).

Due to the shape of the cost function there is the incentive to build large facilities now rather than a sequence of smaller ones in the future (Revelle, 1999). However, if expenditures are sustained in the future, their present worth value decreases. A trade-off must therefore be found between the economies of scale of saving large expansion sizes versus the cost of installing capacity before it is needed (Manne, 1961, Manne AS, 1967). This problem was first analysed by Manne (1961): Figure 5 shows that the expansion in size X increases as α decreases (more economies of scale) and that the higher the discount rate *r* (a percentage defining the time value of money, see following section 1.3 'Engineering economics') the smaller the optimal size of each installation.

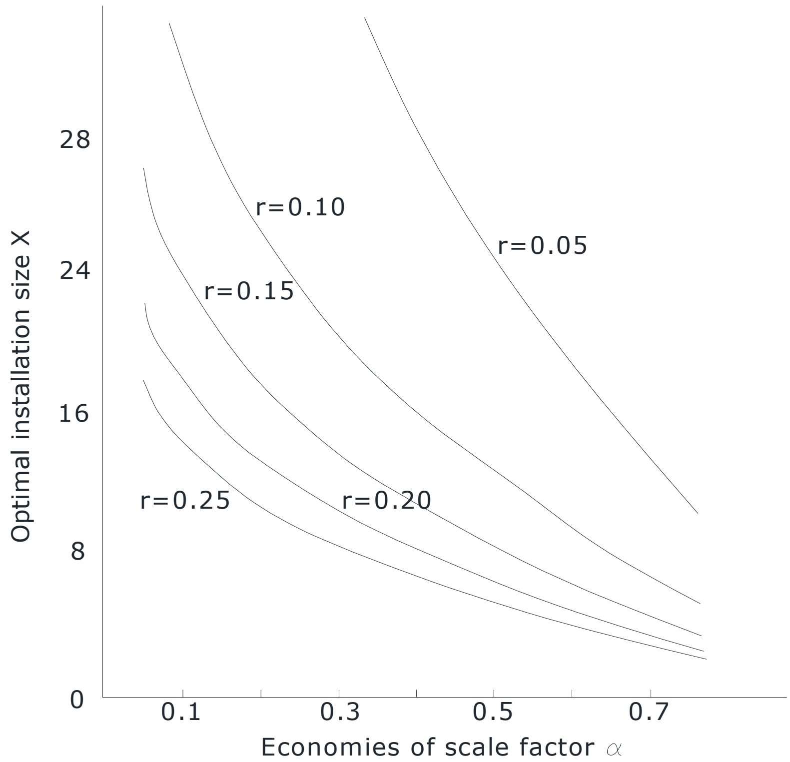

Figure 5: variation of the optimal expansion X with the economy of scale factor α, from (Manne, 1961).

1.3 Engineering economics

Before explaining how the net present value of a future series of payments can be calculated (for example to embed it in the cost function of a capacity expansion problem), the economic engineering concept of 'time value of money' needs to be introduced.

'Money itself is a commodity, and like other goods that are bought or sold, money costs money' (Park S. C., 1997). The cost of money is measured by an interest rate: a percentage applied to an amount of money over a time period. The interest is the charge that the borrower pays to use the lender's property, or can be seen as the benefit that the lender gains by providing the property to another person (Park S. C., 1997). Money can also be invested now to generate more money in the future and this is accounted for in the discount rate, an annual percentage that reflect for the ‘productive uses of money and the effect of inflation’ (Willis R. and Finney B. A., 2003). A higher discount rate implies that a greater weight is placed on current costs and benefits relative to those occurring in the future.

We review below how the future or present worth value of a single payment or a series of payments can be calculated, as this concept appears in later Chapters of this thesis.

The future value F of a single cash flow P can be calculated by using the compound interest method (Park S. C., 1997). According to this method, given an initial cost or benefit P at time zero, the interest I earned in each period is calculated based on the total amount at the end of the previous period. Concisely, if you invested an amount of P at interest rate ic, you would have $P+(ic \times P)=P(1+ic)$ at the end of the first period. Continuing over n periods, the total value of F will grow to $F=P(1+ic)^n$ (equation a) as shown in Figure 6.

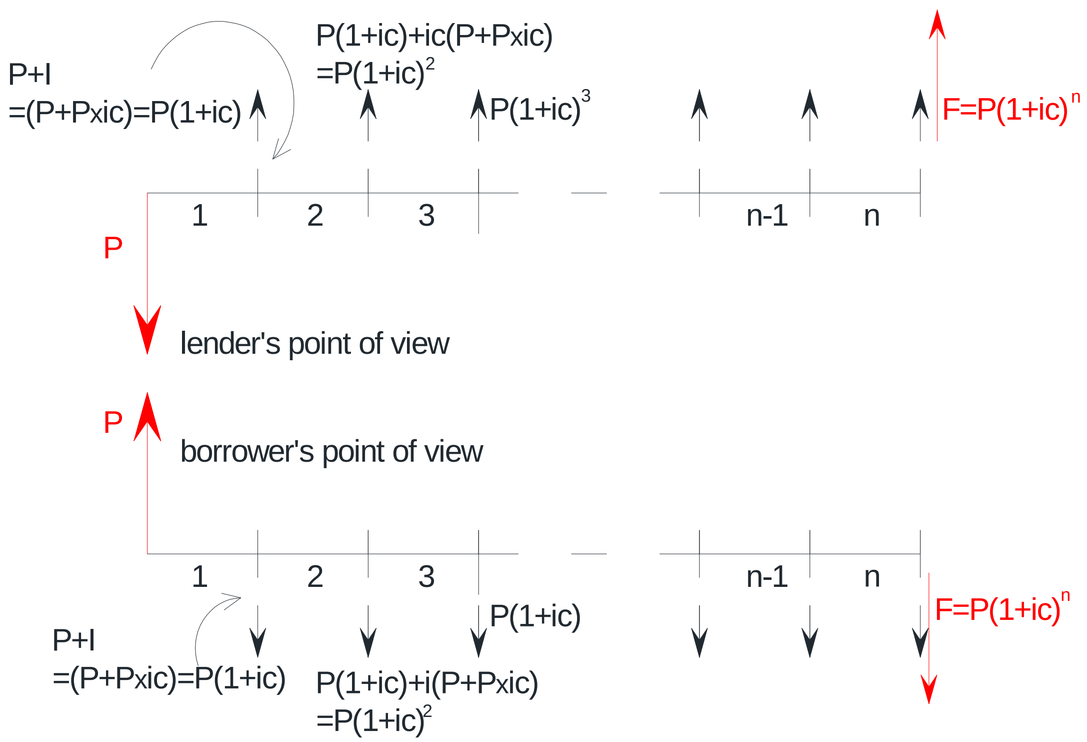

Figure 6: Single cash flow formula, using the compound interest method.

Suppose now that costs or benefits A are uniformly spread over a period of n years. In this case, the future worth value can be expressed as the sum of future worth values of each individual cash flow A (see Figure 7): $F=A+A(1+ic)^{n-1}+\ldots+A(1+ic)^2+A(1+ic)+A$ (equation b). Multiplying this expression by $(1+ic)$ returns: $F(1+ic)=A(1+ic)^n+\ldots+A(1+ic)^2+A(1+ic)$ (equation c). By subtracting equation ‘c’ from equation 'b', the future value of a series of equal payments A is given by: $F=A[(1+ic)^n-1/ic]$ (equation d).

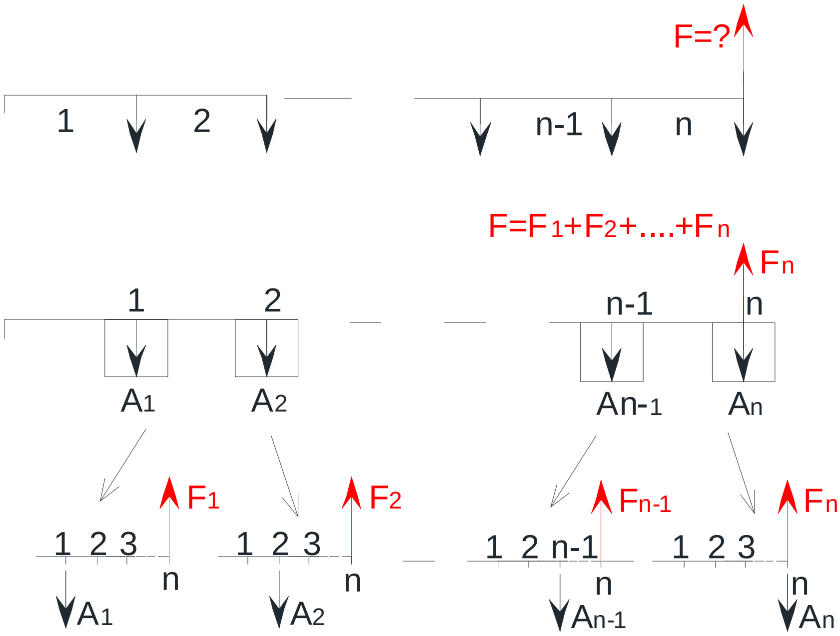

Figure 7: Future worth of an equal payment series A expressed as the sum of future worth values of each individual cash flow.

The present worth value P can then be obtained in two steps: 1. F in equation 'd' is replaced by $P(1+ic)^n$ (see equation a). This gives: $A=P[i(1+ic)^n/((1+ic)^n -1)]$ (equation e) where term $[i(1+ic)^n/ ((1+ic)^n -1)]$ is called capital recovery factor; 2. equation 'e' is rearranged, to return the present worth value P as a function of A. That is: $P=A[(1+ic)^n-1]/[ic(1+ic)^n]$ where $[(1+ic)^n-1]/[ic(1+ic)^n]$ is the present worth factor.

1.4 Modelling approaches

Water supply planning is a classical problem of water resources engineering (Maass et al., 1962). Because of the variety and the complexity of the elements involved, such as the hydrological, institutional and environmental features, there is no single way to approach or such problems. Water resource system management and planning analysis methods can broadly be classified into simulation modelling, optimisation modelling or hybrids. Before explaining each modelling approach in detail, a description is provided bellow about the main differences between simulations versus optimisation models and stochastic versus deterministic methods.

1.4.1 Simulation versus optimisation

Simulation and optimisation models perform complementary roles (Loucks DP et al., 1981 , Loucks et al., 1985, Rogers and Fiering, 1986). Simulation models are used to analyse the impact of a finite number of proposed planning strategies on the environmental system by answering the question ‘what if’. Each strategy is in turn simulated with a mathematical model with rules expressed as mathematical statements to describe the response of the system to a set of environmental, political or management conditions.

Optimisation models identify the solution to a problem, among an infinite number of possible alternatives, by answering the question ‘what’s best’. Among the optimisation modelling approaches, mathematical programming determines the value of a set of decision variables, by optimising an objective function (or set of objectives) subject to a system of mathematical constraints (Castillo, 2002). Decision variables define the variables can be changed by managers to address a management or planning problem. Constraints represent limitations such as on budgets, environmental standards, or resource availability. Since the number of equations is lower than the number of decision variables, the system of constraints is undetermined, meaning that there are infinite solutions to the problem. The objective function helps select among the feasible set of solutions the one that ‘best’ fit the objective function (e.g. minimum cost, maximum profit, etc.). Mathematical optimisation techniques can produce difficulties; in presence of non-linear constraints and objectives, required computational resources may increase and nonlinearities can complicate the identification of a ‘global optimum’ solution (Thomas F. Edgar et al., 2001) meaning that the optimised solution may not be the actual ‘true’ solution to the problem. In contrast to the global optimum, a ‘local optimum’ is a solution which is ‘good’ but not the ‘best’ to a defined problem, where the notion of ‘good’ or ‘best’ relates to the metric specified in the model objective function. In mathematical optimisation modelling there is a class of nonlinear problems, called ‘convex programming’, for which a global solution can be guaranteed. The concept of convexity and its meaning is explained below as it appears later on in this thesis (see Chapter 3).

To explain what ‘convex programming’ problems are it is first necessary to briefly define a ‘convex set’ and a ‘convex function’. Concisely $f(\boldsymbol{x})$ is a convex function if it is always curving ‘upwards’, or more precisely if for any pair of points $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$ on the graph of $f(\boldsymbol{x})$, the function does not have any value larger than the one obtained by the linear interpolation between the two points (see example in panel A of Figure 8 for a function of a single variable). In mathematical terms $f(\boldsymbol{x})$ is convex if, for any scalar γ between zero and one, the following relation holds: $f\,[\gamma\, \boldsymbol{x}_1 + (1\text{-}\gamma)\, \boldsymbol{x}_2] \leq \gamma\, f(\boldsymbol{x}_1) + (1\text{-}\,\gamma)\, f(\boldsymbol{x}_2)$. If in this mathematical statement only the inequality sign holds, than $f(\boldsymbol{x})$ is 'strictly convex'. Similarly if the '≤' sign is replaced by '≥' then $f(\boldsymbol{x})$ is 'concave' (see panel B in Figure 8). A linear function is both convex and concave (but not strictly concave or strictly convex) since for any $0\leq\gamma\leq1$, the equation above is always valid, whether a '≤' or a '≥' sign is adopted. Figure 8 in panel C shows the example of a function defined on a single variable $\boldsymbol{x}$ which is neither convex nor concave because it alternates between curving 'upwards' and 'downwards'. These intuitive definitions of convex and concave functions are stated with further elaboration in (Thomas F. Edgar et al., 2001).

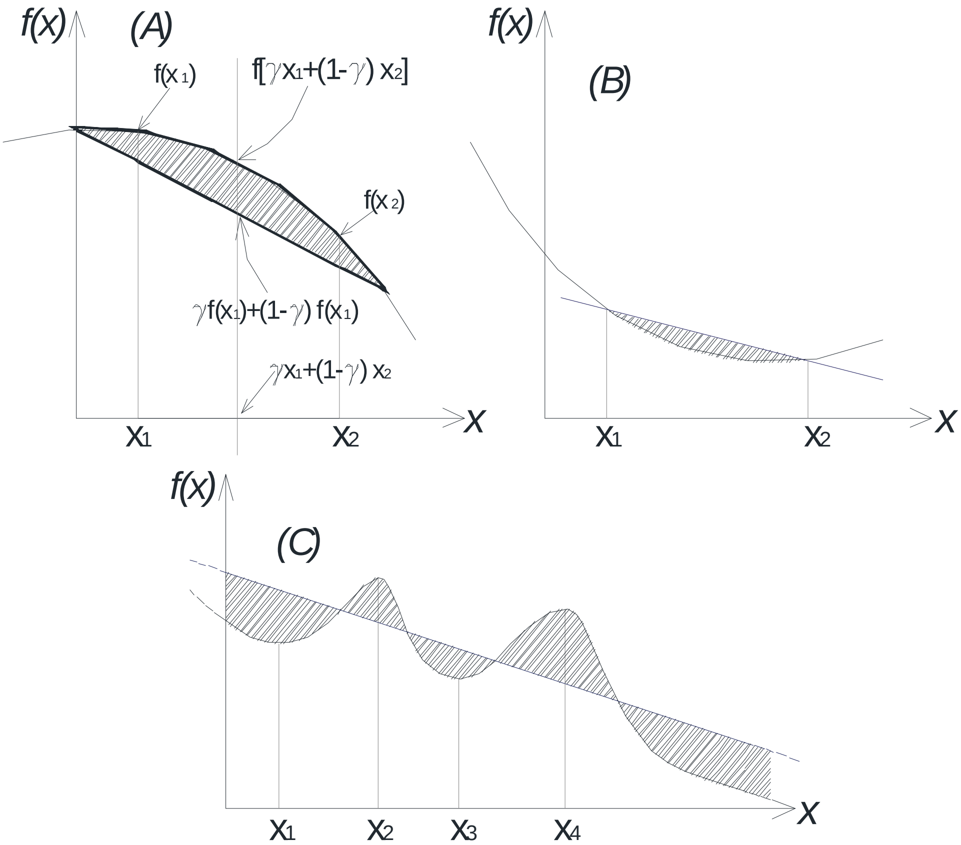

Figure 8: Example of a convex (panel A) and concave (panel B) function of a single variable. Function in panel C is neither convex nor concave. Adopted from (Lieberman, 2004).

If the nonlinear mathematical optimisation problem has no constraints, and the objective function is concave, then a local maximum is also a global maximum (Thomas F. Edgar et al., 2001). At the same way, if the objective function is convex, then a local minimum is also a global minimum. If there are constraints, one more condition is necessary to guarantee global optimality: the feasible region (region of permissible values for ***x*** that satisfy the constraints of the optimisation problem) has to be a ‘convex set’. A set of points is defined as a ‘convex set’ if, for any pair points in the set, the line segment joining the two points is inside the feasible region. In general a feasible region is a ‘convex set’ if each inequality constraints is convex function (Willis R. and Finney B. A., 2003).

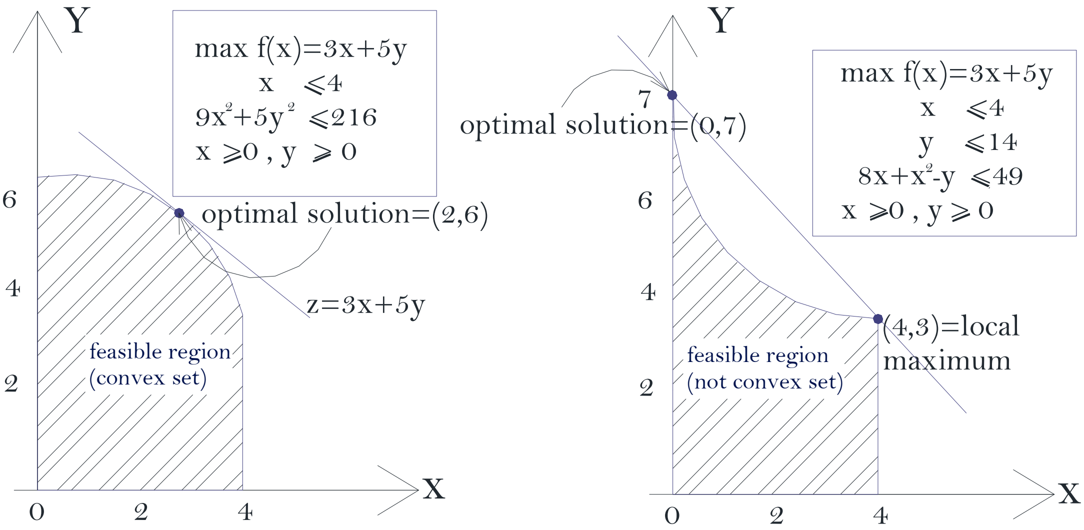

Figure 9: Example of a convex set (panel on the left) and concave set (panel on the right), for a nonlinear programming maximisation problem with two variables (X and Y). Adopted from (Lieberman, 2004).

When it is not possible to solve for a global optimal solution, heuristic methods are commonly used in place of classical mathematical optimisation techniques. A heuristic method search starts with a current trial solution and explores all solutions in the neighbourhood of that point until a better solution if found. If the solution dominates all other solutions in the feasible decision space, then it is a ‘global’ solution, otherwise it is a ‘local’ solution. Heuristic search methods cannot always guarantee global optimality (Willis R. and Finney B. A., 2003), nor it is usually possible to demonstrate that the solution is a global optimal one (Thomas F. Edgar et al., 2001). Metaheuristic methods provide a general structure to develop a specific heuristic search method (Lieberman, 2004) and mainly include: simulated annealing (Kirkpatrick et al., 1983), tabu-search (Glover, 1986), and evolutionary algorithms (Zitzler and Thiele, 1999). A popular technique used in the field of water resources systems is represented by genetic algorithms (Deb et al., 2002), a sub-class of evolutionary algorithms. Genetic algorithms replicate strategies found in nature, such as the process of crossover, selection and mutation (Willis R. and Finney B. A., 2003). Genetic algorithms are ‘population-based’: they work with a ‘population’ of solutions (rather than a single trial solution at a time), and update the ‘population’ when better solutions are found.

1.4.2 Stochastic versus deterministic

Both simulation and optimisation models can be stochastic or deterministic. Deterministic models simplify the problem of incomplete or erroneous data often faced in real word systems. In the deterministic approach, input data are fixed and predictable quantities, and uncertainty of future outcomes is not considered probabilistically, although it can be accounted for with safety factors. In stochastic models some or all input data are random variables and therefore the output is obtained with some range of uncertainty (Lieberman, 2004) as illustrated in the figure below.

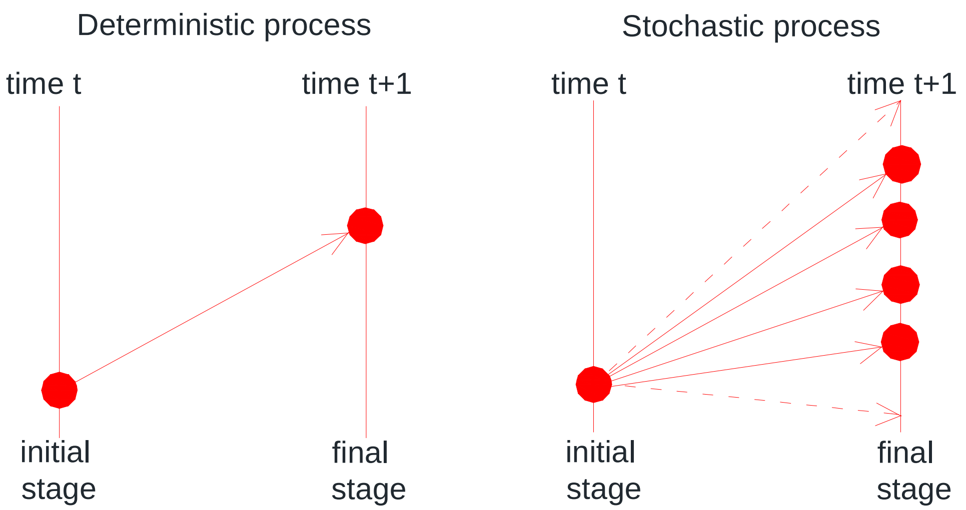

Figure 10: Deterministic and stochastic process, from Lieberman (2004).

The section below reviews the major theoretical simulation and optimisation approaches in the literature, with particular focus on studies conducted on water resources systems planning problems. Benefits and limitations of each method are discussed.

1.4.3 Capacity expansion optimisation modelling

Mathematical optimisation models vary depending with the use of linear or non-linear mathematical formulations, real or integer variables and according to the type of model: static or dynamic (evolving with time) (Revelle, 1999).

Linear programming (Dantzig G. B. and N., 2003) is one of the most popular optimisation methods for the optimal allocation of water resources (Cheng et al., 2009, Hsu et al., 2008, Mousavi and Ramamurthy, 2000, Han et al., 2011). An important characteristic of linear programming is its applicability to large scale problems and the secure convergence to a global optimal solution. In addition to this, linear programming can be implemented through a wide number of available modelling systems like GAMS (Brooke A et al., 2010), LINDO (INC., 2010), LINGO (Schrage, 1999), CPLEX (ILOG, 2007) and MINOS (Bruce A. Murtagh and Saunder, 1983). Linear programming is limited to only using continuous decision variables. In many practical problems some or all of the decision variables may make sense only if restricted to integer values (Lieberman, 2004). An example is when the model decisions are 'yes-or-no' type and are represented in mathematical optimisation by zero/one variables (Mays, 2005). This issue can be overcome by using integer programming (if all the variables have integer values) or mixed integer linear programming (if only some of the variables are integer). Mixed integer programming conveniently allows representing yes/no decisions at each time step and has been widely applied to solve water resources systems capacity expansion problems (Elimam and Girgis, 2012, Labadie, 2004, Labadie et al., 1986, Randall et al., 1997b, Beh et al., 2014).

A limitation of linear programming and mixed integer linear programming techniques is the restriction to use only a linear objective function and linear constraints (Mahmoud, 2006). Even if the assumption of linearity helps avoiding numerous computational difficulties (Mahmoud, 2006), often it does not hold: many water resources systems problems present nonlinearities due to the complex relationships among different physical and hydrological variables or due to nonlinear objectives such as benefits and costs functions. Given the difficulty to incorporate into a linear model all the complexity of the system and all the objectives considered important to the stakeholders, nonlinear programming methods have often been applied to water resources systems planning problems (Kim and Hopkins, 1995, Barros et al., 2008). Non-linear programming however may presents numerical difficulties related to the research of the global optimal solution (see 'convex programming' in section 1.4.1). Such issues may be overcome through linear approximation of the nonlinear constraints and the nonlinear objective function (Willis R. and Finney B. A., 2003). A commonly used method is the piecewise linear approximation which is also implemented in Chapter 3.

Dynamic programming is an optimisation approach well suited to tackle nonlinearities. Dynamic programming is a method introduced by Bellman (1957) and consists of decomposing a complex multistage problem into a series of simple sub-problems then solving them recursively. Dynamic programming is one of the most frequently used techniques in water resources systems analysis (Braga et al., 1985, Chou et al., 2013, Dandy et al., 1984, Hsu et al., 2008, Luo et al., 2007, Mahmoud, 2006), however its application to large scale problems may be limited due to the ‘curse of dimensionality’ problem (Bellman, 1957): the computational difficulty of these algorithms quickly increase with the number of state variables. (Yakowitz, 1982) reviewed the application of dynamic programming for water resources development and management problems.

The optimisation techniques described above have proven valuable to address a wide range of practical capacity expansion problems, however when applied to large scale systems, optimisation models can face challenges (Fiering et al., 1986, Yates et al., 1984). The computational complexity may depend on several different factors, such as size and topology of the network, and the type of hydraulic relationships involved in the problem (Cembrano et al, 2000). When this is the case heuristic optimisation techniques can be used to search for good feasible solutions reasonably ‘close’ to the optimum. These methods cannot guarantee the convergence to a global optimum solution, however are most commonly used to overcome complexities such as non-linearity, discontinuity and discreetness which often limits the application of traditional optimisation techniques. Application of this technique to water resource systems planning problems can be found in (Savic and Walters, 1997, Deb, 2001, Farmani et al., 2005).

1.4.4 Capacity expansion optimisation under uncertainty

Water resource systems are often associated with many uncertainties due to the stochastic nature of metrological processes such as evaporation, rainfall and temperature. In addition, future populations and economic forces, priorities for water uses and irrigation patterns cannot be known with certainty (Daniel P. Loucks et al., 1981, Lempert et al., 2006, Lempert and Collins, 2007). Consideration of uncertainty in water resource systems is essential under climate change and increasing water scarcity. To consider uncertainty stochastic approaches can be used where some data elements are ‘random’ and the output is obtained with some range of uncertainty (Lieberman, 2004).

Sensitivity analysis is a ‘reactive’ method to control uncertainty: it measures the sensitivity of the solution as the input data change under uncertainty (it quantifies locally the stability of the solution with respect to data perturbation) but does not provide any mechanism to control such sensitivity (Mulvey et al., 1995). Contrary to sensitivity analysis, stochastic programming is a ‘proactive’ approach: a set of decision variables are used to adjust the model solution once the uncertain parameters are observed. Two main approaches to optimisation under uncertainty are used: stochastic programming, also known as recourse models, and robust stochastic programming. Programming with recourse dates back to Dantzig (1955). Under this approach the decision variables are subdivided into a first-stage and a second-stage set. The first-stage variables are defined prior to the realisation of the uncertain parameters, while the second-stage or recourse variables are used to improve, at certain cost, the model solution once the uncertain parameters are observed. The recourse variables can therefore be considered as 'corrective measure' against the infeasibilities that may arise under uncertainty (Sahinidis, 2004). Because of the uncertainty, the second-stage cost is a random variable. The objective function then minimises the sum between the first-stage costs and the expected value of the random second-stage costs. Concisely, *recourse* models determine a solution that can be adjusted under uncertain events at minimum cost.

When uncertainties are unpredictable, cautious decision-makers should look for 'robust' planning solutions that are that are 'good' under a wide range of scenarios. Robust stochastic programming can therefore be used to return a solution which remains close enough to optimality when input data change. In robust optimisation, the objective function of the *recourse* model is augmented by a term, such as the variance, which measures the variability of the second stage costs. Such a term is then multiplied by a non-negative scalar 'omega'. Large values of 'omega' produce solution with a lower variance, while smaller values of 'omega' reduce the expected costs. By executing multiple runs with different values of 'omega', a trade-off curve can be obtained which tracks the cost of the solution versus its robustness (Mulvey et al., 1995). Robust optimisation was first introduced by Soyster (1973) for linear programming problems. The main limitation of the Soyster method was its over-conservatism: the method admits the highest protection against uncertainty by considering all uncertain parameters taking their worse value (Bertsimas and Sim, 2004). Further extensions to the method were developed by (Ben-Tal and Nemirovski, 1999, Ben-Tal and Nemirovski, 2000, El Ghaoui et al., 1998, ElGhaoui and Lebret, 1997) to address this issue. These lead to the definition of new non-linear, although convex, models which are more computational demanding than the Soyster method (Ben-Tal and Nemirovski, 2000). A different approach to robust optimisation was proposed by Bertsimas and Sim (2004) for solving mixed integer linear programming (MILP) problems under data uncertainty. The method claims to retain the advantages of the approach proposed by Soyster, without changing the type and complexity of the problem. It assumes that the uncertain parameters follow an unknown but symmetrical distribution, bounded by an internal variable called ‘the price of robustness’.

Stochastic optimisation (recourse models and robust stochastic programming) has found numerous applications for capacity expansion problems (Malcolm and Zenios, 1994, Laguna, 1998, Bai et al., 1997) (Ahmed and Sahinidis, 2003, Bean et al., 1992, Berman et al., 1994, Shabbir Ahmed et al., 2001) and water resource systems capacity expansion under uncertainty (Chung et al., 2009, Cunha and Sousa, 2010a, Cunha and Sousa, 2010b, Watkins and McKinney, 1997, Guo et al., 2009, Sechi and Sulis, 2009, Li et al., 2008, Maqsood et al., 2005, Rosenberg et al., 2008).

1.4.5 Simulation modelling and its use in capacity expansion problems

Simulation models are used to analyse the impact of a finite number of pre-defined proposed strategies. Analysts first identify a list of portfolios using engineering and economic considerations. Each portfolio is then simulated with the simulation model. User-defined operating rules that describe the behaviour of the environmental system are included (from which the name of ‘rule-based simulation’ models). The model results return a detailed description of how the system is affected under each plan. Traditional measures of system performance, such as reliability, resilience and vulnerability (Hashimoto et al., 1982) can be evaluated during the simulation and compared over the different portfolios. Scenario analysis can determine whether or not the strategy is ‘robust’, that is if under a range of scenarios the tested plan works acceptably.

Simulation models provide only localised information about the analysed system: only one set of conditions is considered in the analysis. Simulation rules can quickly become complicated often requiring thousands lines of computer code to be described in detail. In presence of a large number of option configurations and operating rules, repetitive applications of the model can be time consuming (Willis R. and Finney B. A., 2003). To overcome this problem simulation models have often been used in combination with optimisation techniques in order to screen the many possible system implementations (Rani and Moreira, 2009). Another hybrid use is called ‘optimisation-driven simulation’, where an optimisation model is used to solve the allocation problem at each simulated time-step. Previous studies on large scale networks showed that linear programming based simulation models can simplify the simulation process (Chaturvedi and Srivastava, 1981, Labadie, 1993). (Randall et al., 1997a) use a mixed integer programming model to simulate the long-range planning of the Almeda County water district in California.

Besides traditional mathematical optimisation techniques, metaheuristic methods, such as evolutionary algorithms, have also been used in combination with simulation models (Jamieson and Fedra, 1996). In this case, each time the heuristic search algorithm evaluates a solution, the simulation model is run to determine the solution's performance.

Simulation models have a long history in water resources planning problems and are often incorporated in 'decision support systems'. Decision support systems are defined as interactive computer based systems that enable the decision-maker to use data and models that search for a solution to a 'poorly or insufficiently structured problem' (de Kok and Wind, 2003). A wide range of water resources modelling software exist for rule-based simulation such as IRAS (Matrosov et al., 2011, Loucks et al., 1995), Aquator (Oxford Scientific Software, 2008, Vamvakeridou-Lyroudia et al., 2010), WaterWare (Jamieson and Fedra, 1996) and 'optimisation-driven simulation' approaches such as MISER (Fowler et al., 1999), WEAP (Yates et al., 2005) and CALSIM (Draper et al., 2004). Further information about this type of 'decision support systems' can be found in (Wurbs, 2005). A WaterWare extension (Cetinkaya et al., 2008) and Aquator-GA (Vamvakeridou-Lyroudia et al., 2010) use water resources simulation models imbedded into heuristic optimisation.

Each modelling approach has advantaged and disadvantages. Choosing which of the above models to apply can be linked to specific modelling requirements or to the institutional context which may determine which approach is more appropriate to a particular application. For example, 'rule-based simulation' and 'optimisation-drive simulation' may not explicitly support capacity expansion decisions and are usually adopted for modelling system operations in detail (such as reservoirs releases and water allocation).

1.4.5.1 Monte Carlo simulation

Monte Carlo simulation is a type of stochastic simulation usually adopted when system inputs can be described by probability distribution functions (PDF). With the Monte Carlo method the system can be simulated by sampling from the PDF. This process is repeated many times and a distribution of outcomes is obtained. The accuracy of results improves as the number of repetitions increases. Monte Carlo simulation has been applied for several capacity expansion planning problems of several public sector utilities (Renna, 2013, Tekiner et al., 2010, Yang and Wen, 2005, Hasani-Marzooni and Hosseini, 2011). This method is also established for water resources planning problems (Maass et al., 1962). Prudhomme et al. (2003) used Monte Carlo simulation to randomly generate climate change scenarios and analyse their potential impact on five catchments in Great Britain; Zhang and Kennedy (Zhang and Kennedy, 2006) applied Monte Carlo simulation to reduce uncertainty on the yields of groundwater resources in Beijing. Monte Carlo simulation can also be used with equiprobable ensembles (Lopez et al., 2009) when PDFs are unknown.

1.5 Capacity expansion planning in the English water industry - the EBSD framework

Since 1989 England is served by 22 privatised water companies (utilities) which operate as regulated natural monopolies. Their abstraction from the environment is controlled by the Environment Agency (EA), while the companies' consumer prices and investments are regulated by Ofwat (the water services regulation authority). Water companies must demonstrate regulators their plans to meet future demands are best value and maintain environmental standards or justify other considerations that move away from these criteria. Companies 'Water resource Management Plans' (WRMPs) must follow regulatory guidance (EA et al., 2012a, EA et al., 2012b) and typically use the Economics of Balancing Supply and Demand (EBSD) framework to generate socially efficient least economic cost water resources supply plans (UKWIR, 2002a, UKWIR, 2002b).

Water companies apply the EBSD approach individually, but in some cases also collectively in regional applications. Early on in this PhD project an opportunity arose to work with a group of companies looking at regional infrastructure investment (described in Chapter 2). We discuss this application below before providing more background on the EBSD approach.

The water companies operating in South East England (see Figure 11) have a history of working together as the Water Resources in the South East (WRSE) Group (von Lany et al., 2013). South-East England is the driest part of the UK with the largest and fastest growing population. The WRSE Group includes: the Environment Agency, Ofwat the

Consumer Council for Water and Defra (Department for Environment Food and rural Affairs).

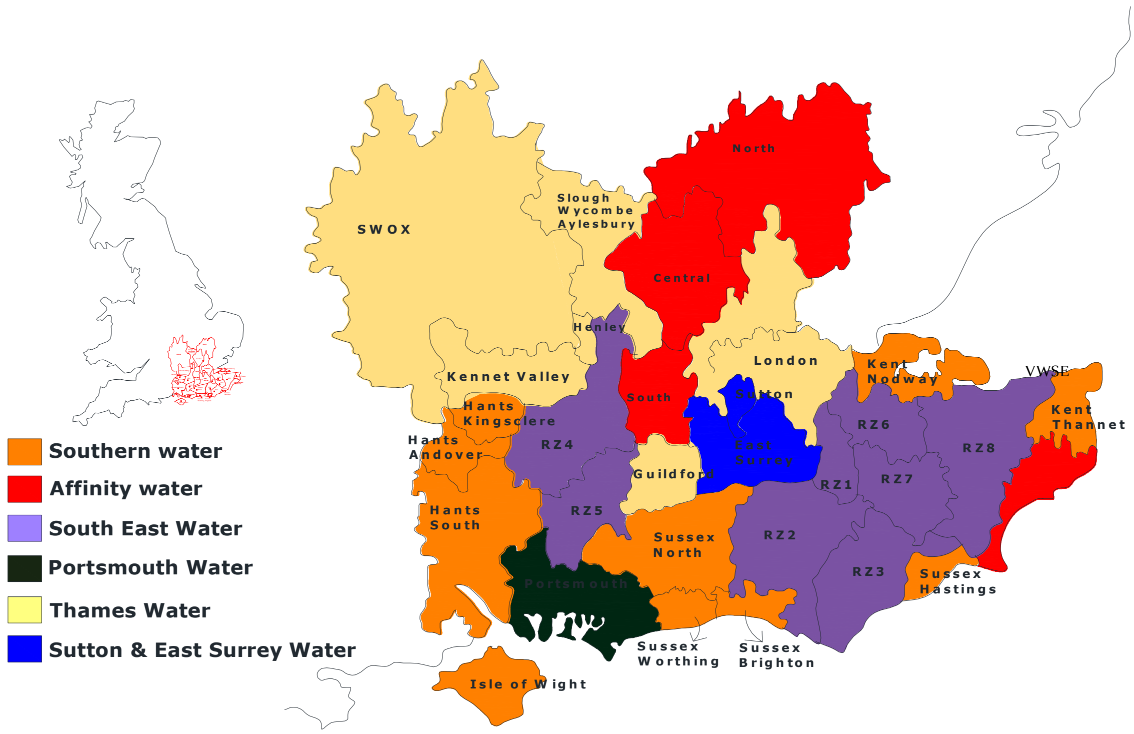

Figure 11: Water companies and water resource zone in the 'Water Resources of the South East' network.

The WRSE group's aim is to explore new opportunities for water companies to share resources through new bulk supply agreements and other joined up investments. The group undertakes capacity expansion modelling for their combined area following the EBSD framework (EA, 2005b, EA, 2010b, R. Critchley and D. Marshallsay, 2013). The idea behind the WRSE model is to encourage water companies to adopt the solution to the region supply-demand balance problem identified by the optimisation model (EA, 2010b). Regional modelling carried out in 1990 led to the implementation, by 2005, of four new inter-company interconnections. In 2010 the WRSE group identified that a possible savings of £M 501 could be reached by 2035 if a greater level of sharing of resources was allowed in the South East (EA, 2010b). In 2013, the WRSE group has carried out a new phase of regional modelling (R. Critchley and D. Marshallsay, 2013). The 2013 WRSE model was developed by the thesis author and is introduced in Chapter 2.

The EBSD planning framework outlined in the sections below provides the structure within which the WRSE model operates.

1.5.1 Estimating supply and demand

The water supply planning process in England and Wales considers a 25 to 30 year planning period and uses a Water Resource Zone (WRZ) spatial scale. The Environment Agency (EA et al., 2012a) has defined a WRZ as:

'*The largest possible zone in which all resources, including external transfers, can be shared and hence the zone in which all customers experience the same risk of supply failure from a resource shortfall.'*

The firm yield (referred to in England as 'deployable output') of existing and potential future sources of supply is defined (EA et al., 2012a) as:

'The output of a commission source or group of sources or of bulk supply as constrained by the environment, licence if applicable, pumping plant and/or well/aquifer properties, raw water mains and/or aquifers, transfer and/or output main, treatment, water quality'.

Deployable output is therefore an annual volume per source that companies opine they can rely on even under worse-case conditions. Water companies estimate deployable outputs by using detailed water resource system simulation models that track flow and storage at regular intervals of time (e.g. daily or weekly). Such models are used to represent the complex aspects of water resources systems such as hydrology and system operating rules, minimum environmental flows and other relevant hydrological, engineering, and institutional factors. Yields are assessed by looking at long-records data of rainfall, direct river flow, groundwater levels or any other information available. Historical records must looks back at least till year 1920 so to include a 'sufficient variety of conditions and most of the known severe droughts in the last one hundred years'(EA, 2008, EA et al., 2012a). When estimating the deployable output, water companies assume a certain level of service (frequency of supply failures) which they are meant to have agreed on with their clients. Companies' deployable output is therefore dependent on the system's reliability (probability of water deficits). A higher reliability corresponds to lower values of the deployable output. Once the deployable output is estimated, a number of adjustments are made to determine the 'water available for use' as shown in Table 1. Among these adjustments, the outage allowance is a temporary loss of deployable output

(UKWIR, 2002a) due to unplanned or planned events (such as maintenance or an unexpected pollution incident), while sustainability reductions are reductions in the deployable output imposed by the Environment Agency to meet statutory and environmental requirements (see Table 1).

Water companies estimate future demands by methods such as regression based on historical trends, micro-component analysis or expert judgment (UKWIR, 2002a, UKWIR, 2002b). Water companies are usually able to provide reasonably accurate estimates for the non-household demand as the majority of these users are metered. A range of information is available about past trends of demand for measured households and this data can be used as guide to generate future trends (McDonald et al., 2003). A greater level of uncertainty surrounds estimates of unmeasured household demands. Most companies estimate unmeasured household demand by conducting domestic consumption studies, whose 'scale, purpose and design' changes from company to company (McDonald et al., 2003). Often 'micro-component analysis' is used to analyse water usage (frequency, volume, uses) for different household types and generate future trends based on population forecast (UKWIR, 2002a, UKWIR, 2002b). Demand estimates are done on an annual basis, considering dry year scenarios (periods of low rainfall without demand restrictions), normal weather patterns (EA et al., 2012a) and any other scenarios the company considers relevant to the supply-demand planning problem. Two levels of dry year demands are usually quantified: dry year annual average demand (DYAA) and the dry year critical period (DYCP) demand (see Figure 12). The DYCP demand is included in the companies' capacity expansion planning problem only if it drives the need to implement new supply or demand management measures (EA et al., 2012a) and is defined as the average demand over a 'peak demand period', typically a week (see Figure 12). The normal year annual average (NYAA) demand represents the average demand over a year with normal weather patterns. Another scenario usually considered is the minimum deployable output (MDO) which applies when supplies are expected to be at their minimum (see Figure 12). This normally occurs in autumn when river flows and/or groundwater levels are at their lowest level and sources operate close to their minimum deployable output.

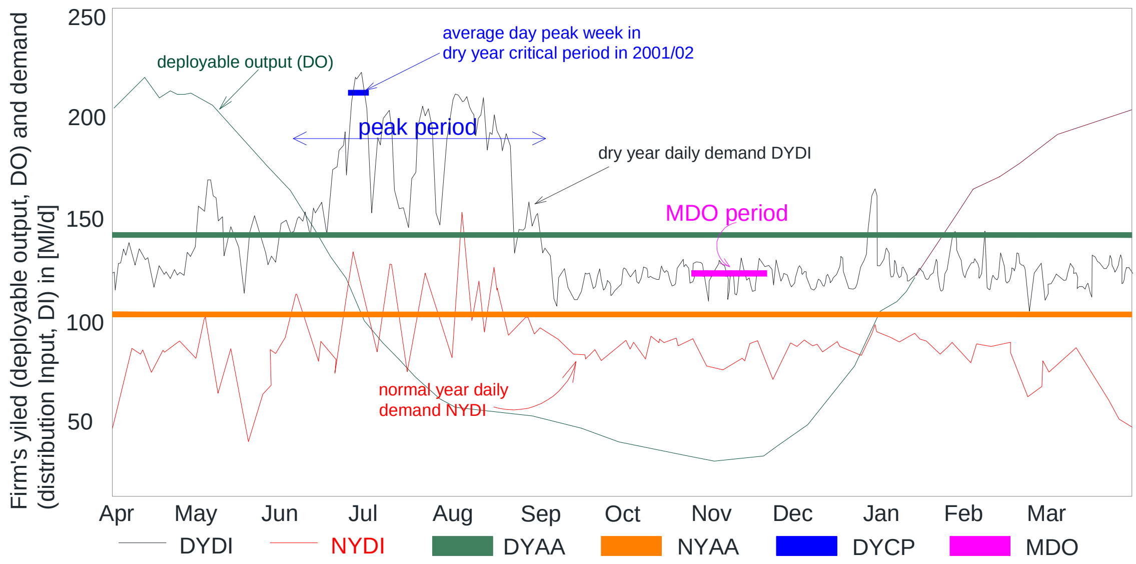

Figure 12: Definition of annual demand scenarios (NYAA, DYCP, MDO and DYAA) [adapted from (Southeast Water, 2009)]. DYDI is the dry year daily demand as quantified by distribution input (DI), i.e. what companies input to their networks, NYDI is an example of normal year daily demand.

Components of demand and supply that must be estimated per WRZ are listed in Table 1.

- Water delivered and billed (measured and unmeasured household and non household demand)
- +Distribution system operation
- +Distribution losses
- +water taken unbilled *(legally and illegally)*

=Total demand(distribution input)

- Deployable output
- -Sustenability reductions
- - Outage allowance
- +bulk imports
- -bulb exports

=Water available for use

Table 1: Elements of demand (left) and supply (right) balance as relevant in the water industry of England and Wales (UKWIR, 2002a).

In the table above, the *distribution system operation* in the left box is the 'water knowingly used by the company to meet its statutory obligations particularly those relating to water quality' (EA et al., 2012a) such as main flushing and air scouring. The dis*tribution losses* are the sum of losses in trunk and distribution mains, service reservoirs and communication pipes (EA et al., 2012a).

1.5.2 Treatment of costs

The 2012 from the Environment Agency (EA et al., 2012a, EA et al., 2012b) requires companies to estimate costs of assets over their whole useful life, and not only over the 25 to 30 years planning horizon. For example, given a 25 year planning period, if an asset with an 80 year economic life is activated at the 25th year then the EBSD model would have to consider a total period of 105 years to embed such costs in the net present value calculation.

1.5.3 Dealing with uncertainty

Because current and future supply and demands are uncertain, the EBSD method considers a safety factor called 'headroom', which aggregates all sources of supply and demand uncertainty into an annual estimate per WRZ (UKWIR, 2002c). Headroom is the difference between the water available for use and the estimated demand for each WRZ. Target headroom values are estimated by water companies in the following way. First the company identifies, for each WRZ, all sources of uncertainty on supply and demand estimates, following the UKWIR report (2002c). Specifically, the UKWIR report identifies nine supply-related (S1 to S9) and four demand-related (D1 to D4) sources of uncertainty (see Table 2). These are referred to as 'headroom components'. Current guidelines exclude components S1, S2, S3 and S7 from the final assessment of headroom (Hall et al., 2011).

Headroom component of uncertainty		Description
Type	Headroom component	
Supply related	*S1*	Vulnerable surface water licences
	S2	Vulnerable groundwater licences
	S3	Time-limited licences
	S4	Bulk imports
	S5	Gradual pollution of sources causing a reduction in abstraction
	S6	Accuracy of supply side data
	S7	Single source dominance
	S8	Uncertainty of impact of climate change on source yields
	S9	Uncertain output from new resource development
Demand related	*D1*	Accuracy of sub-component data
	D2	Demand forecast variation
	D3	Uncertainty of impact of climate change on demand
	D4	Uncertain outcome from demand management measures

Table 2: Headroom components listed in 'an improved methodology for assessing headroom' (UKWIR, 2002c)

Probability distribution functions (PDF) of uncertainty are then assigned to each headroom component (UKWIR, 2002d). PDFs can take the form of a triangular distribution or any other function that best fits the available information (such as normal, log-normal exponential, discrete distributions). The combined headroom uncertainty (HU) in equation 1.1 (UKWIR, 2002d) is then estimated by using Monte Carlo simulation.

$$HU = S4+S5+S6+S8+S9+D1+D2+D3+D4 \tag{1.1}$$

The Monte Carlo simulation, randomly selects values from the PDFs assigned to each headroom component. The sampling is executed for each year of the planning horizon and for each WRZ and is stopped after a determined number of iterations, set by the user. A typical number of 5000 trials is usually considered (UKWIR, 2002d).

When sampling from PDFs, possible correlations among the data values must be considered. UKWIR (UKWIR, 2002d) provides guidelines for assessing the correlation coefficients when there are no data available to calculate it directly. A typical list of correlated headroom components is also reported in the UKWIR report (2002c). These include: 1. positive correlation between the S1 components of two sources belonging to the same catchment and affected by the same licence loss issue; 2. negative correlation between the S1 and S2 components of two sources in the same catchment: the greater the licence loss on S1, the less likely is S2 to suffer from a licence loss 3. positive correlation between the S8 and D3 components as both supply and demand might be influenced by the same process such as climate change.

Results from the Monte Carlo analysis for each year and WRZ, return the overall headroom uncertainty in the form of percentiles (see Figure 13). Each point in time on the *x* axes represents a unique PDF that describes the uncertainty at that time.

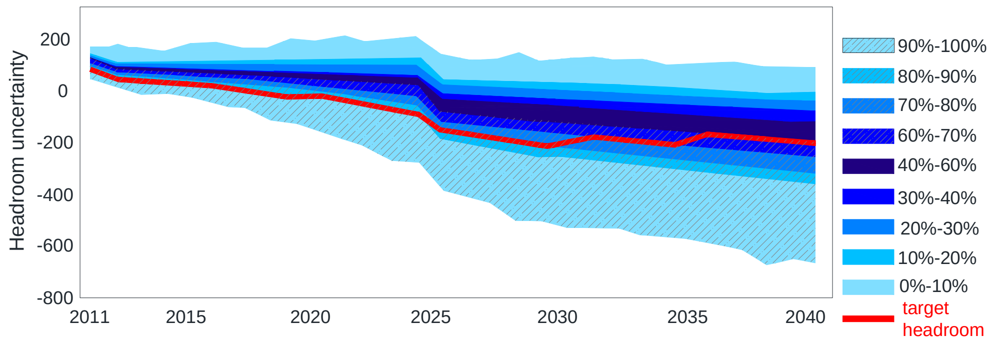

Figure 13: Headroom uncertainty from Monte Carlo simulation and target headroom profile (from 90% percentile falling to 60% percentile), adapted from (Southeast Water, 2009).

Each percentile Y of the headroom uncertainty (say the 90^{th} percentile), ensures that there is a Y% (that is the 90%) likelihood that the supply-demand balance will not be in deficit. A target headroom risk profile (see red line in Figure 13) is then chosen by the water company. In the early years of the planning period, values corresponding to higher percentiles of the headroom uncertainty are usually chosen than in later years: in the short term period companies are usually prepared to accept a low level of risk about their capability to maintain the security of supply because there is a little lead time for supply and demand management schemes to be completed. Also, short term uncertainties are more ‘realistic’ than long term ones since in the short term predictions there is a higher level of supporting evidence (Southeast Water, 2009).

1.5.4 Least-cost solution to the planning problem

Analysis of supply and demand over the planning period may identify supply-demand imbalances (see Figure 14). If there are imbalances, planners must then identify the widest possible range of feasible options to re-establish the supply-demand balance.

Next, costs of each proposed option are estimated. Financial, environmental and social costs must be considered. Financial costs are divided into capital expenses (‘capex’) and operating expenses (‘opex’). Capital costs can include the purchase or disposal of fixed assets (e.g. pipeline and storage tanks), land purchases and the replacement of physical structures. Operating costs can be fixed (e.g. fixed operation and maintenance costs, ‘fopex’) or variable (e.g. pumping, treatment and labor costs, ‘vopex’) as stated in (UKWIR, 2002a). For practical reasons companies are asked to cost and size discrete schemes rather than use continuous cost curves.

At this stage, an algorithm must be selected to choose the least financial, social and environmental cost solution (schedule of supply and demand management measures to meet any supply-demand imbalances). AISC is a simple method that does not guarantee an optimal (least cost or maximum benefit) solution. The average incremental cost (AIC) of an option is defined as the net present value of all option costs, divided by the net present value of the options capacity, or forecasted output (UKWIR, 2002a, UKWIR, 2002b).. If the option costs include also the environmental and social costs, the result is the Average Incremental Social Cost (AISC). Ranking the individual options in ascending AISC order provides the indication of the least-cost solution to the identified planning problem.

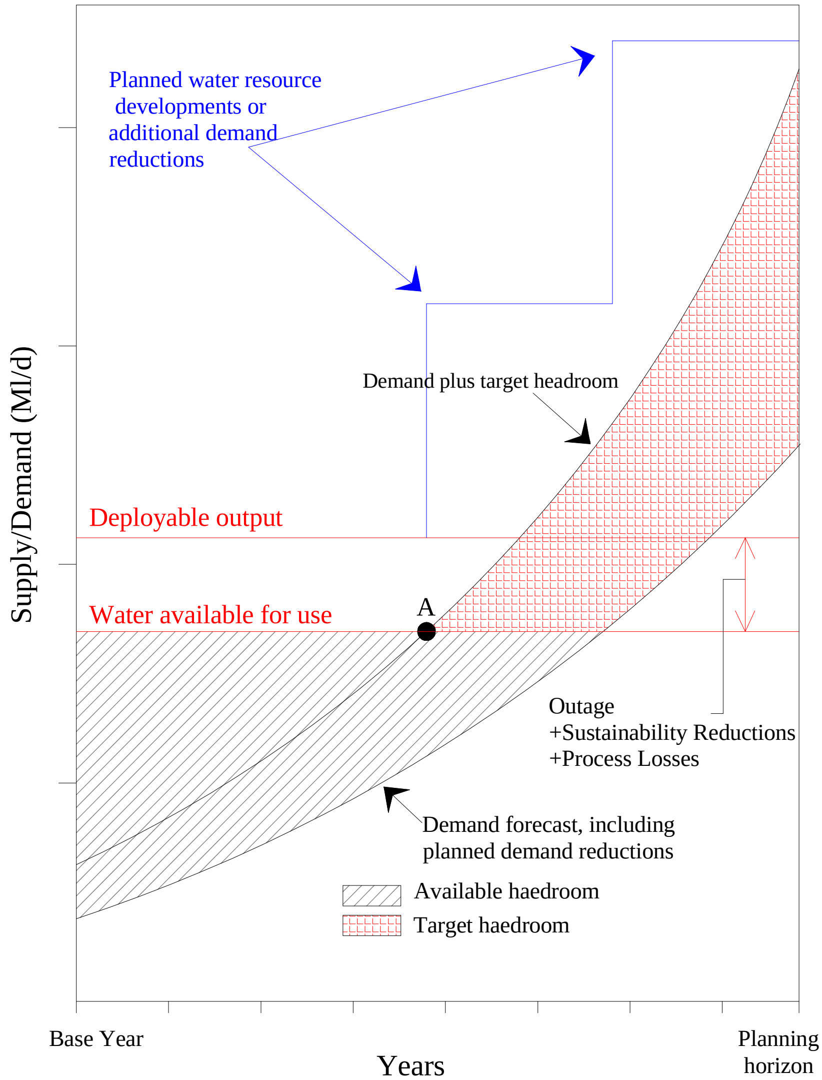

Figure 14: The supply demand balance as considered in the England water planning [adapted from (UKWIR, 2002c)]. Demand plus target headroom must be greater than water available for use (yield of 'deployable output', minus losses, outage and sustainability reductions).

Another technique proposed in the EBSD guidelines is to formulate linear/integer programming optimisation models. When there is a combination of integer and real variables a mixed integer linear program (MILP) can be used. In practice MILP is the most frequently used search method for EBSD applications.

1.5.5 Choice of EBSD modelling framework

Different modelling frameworks within the EBSD approach can be applied. The 'Current Framework' is the most used in industry practice. In the 'Current Framework', supply and demand estimates are fixed and all sources of uncertainty are included into the annual safety factor called target headroom (THR). Target levels of service are also fixed, and the method is deterministic – only one version of the supply/demand future is evaluated to select options. Target levels of service, agreed between the companies and their customer, set out how frequently a water company expects to impose restrictions in the use of hose-pipes, sprinklers and other non-essential uses. Target levels of service are usually stated in terms of the maximum likelihood that a particular restriction will need to be imposed (e.g. a particular restriction will need to be imposed no more than 1/N years). This approximates to an annual probability of less than 1/N that a particular restriction in supply will need to be applied.

An expansion of the ‘Current Framework’ is the ‘Intermediate Framework’ that can be used to test the reliability of a solution set provided by the deterministic EBSD model using Monte Carlo simulation. The reliability of a water system is the probability that, under a given plan, supply will fail to meet the demand. In such a situation, customers might experience a restriction on the supply of water, the severity of which depends on the size of the shortfall in supply. Monte Carlo simulation uses random sampling from known or estimated probability distributions functions of uncertainty applied to the supply and demand values of the solution set provided by the EBSD model. The sampling is repeated many times and a distribution of outcomes (imbalances between supply and demand) is obtained. This provides a measure of the level of service that the options in the solution set should provide. The predicted level of service is then compared against the company’s target level of service. If they are equal or sufficiently close, the EBSD model’s solution (investment plan) stands. If the predicted level of service is too high, then target headroom is decreased and the algorithm is run again. On the contrary, if level of service is too low, headroom is raised and the EBSD model is run again.

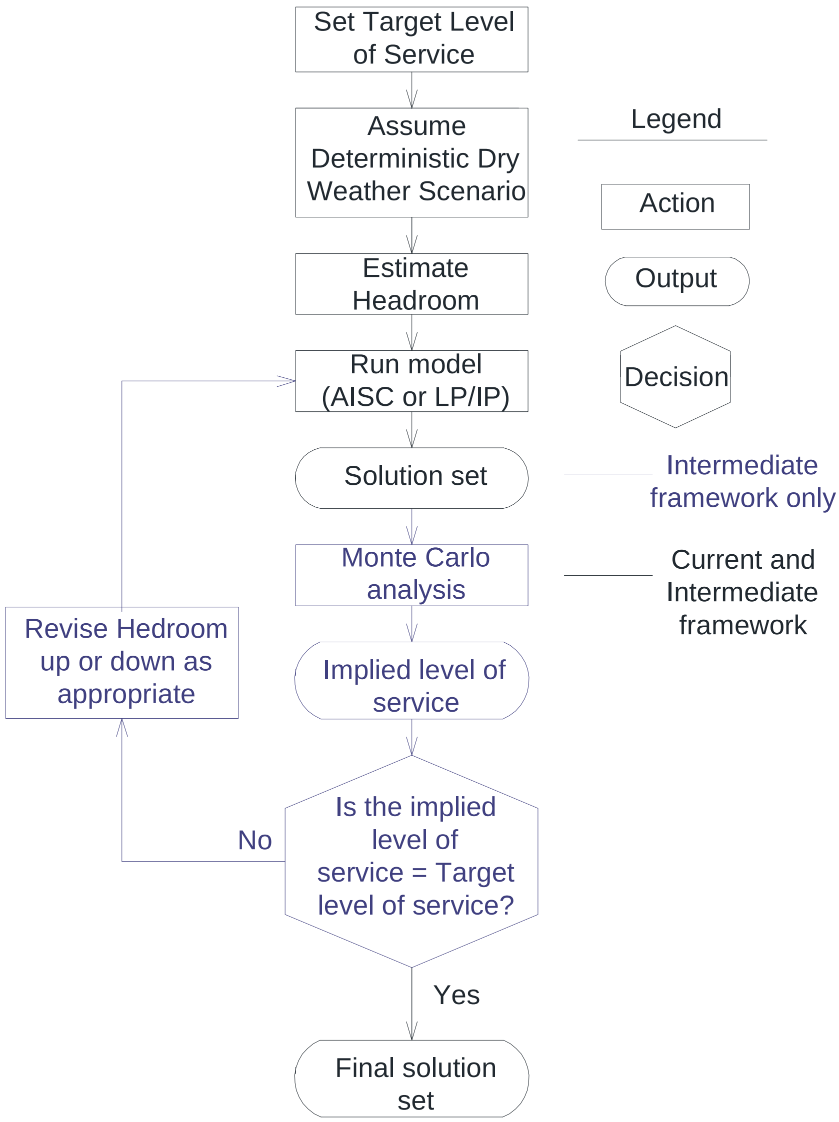

Figure 15: The Current and intermediate framework, adopted from UKWIR (2002a).

1.6 EBSD framework discussion

1.6.1 EBSD benefits

The EBSD framework is currently used by water companies in England to identify 'socially efficient and least-cost' investment decisions (UKWIR, 2002a, UKWIR, 2002b). It has some clear benefits that are discussed below.

The EBSD framework has been widely adopted by the water industry in England because of its relative simplicity, parsimony and applicability to large scale systems with complex interdependencies. Capacity expansion models are typically hard to solve because building new infrastructure has economies of scale which makes the optimisation model non-convex with potentially complications for solving it in practice (see section 1.4.1). Non-convex problems arise when costs are represented as a concave function of capacity. Within the EBSD framework this problem is overcome by fixing the design capacity and costs of proposed schemes, i.e., considering discrete costed schemes rather than continuous capacities. An optimisation model is then used to select the least-cost schedule of discrete system upgrades. Considering discrete schemes in place of the original cost function can lead to sub-optimal results as the truly optimal level of option implementation is unlikely to be present in the pre-specified set of discrete options. This would be a limitation except for the fact that water companies and regulators prefer costing discrete schemes as they are unwilling or unable in many instances to generate continuous cost curves, which in practice can be challenging to generate accurately.

Perhaps the main strength of the EBSD approach is its institutional appropriateness; the EBSD framework allows water companies to defend their investment decisions to regulators who require them to maintain the supply-demand balance at least economic cost. Given the challenges encountered in using optimisation models for real-world water resource planning (Fiering et al., 1986), the fact that EBSD is embedded into national planning is an unusual success in water resource system optimisation. The simplicity and parsimony of the framework contribute to its wide application. EBSD uses available data and its results are readily understood. EBSD models consider large numbers of feasible options just as they are presented to regulators and estimated by companies: one price linked to one capacity. Furthermore, in addition to deriving the least-cost portfolio considering all proposed options, it also provides the least-cost annual schedule of system upgrades over the planning period, exactly what financial planners and regulators ask for.

The benefits listed above mean that EBSD is a worthy starting point for water supply system capacity expansion modelling in England. Next we describe EBSD limitations and some issues related to its application in order to motivate the thesis research.

1.6.2 EBSD issues and limitations

Work in Chapter 2, a full scale regional application of EBSD, allowed to identify some EBSD limitations and issues which are summarised below to justify the subsequent thesis research questions. The EBSD issues and limitations addressed in this thesis are listed below in the same order as they are presented in the following Chapters. Issues introduced in sections 1.6.2.1 and 1.6.2.2 are addressed in Chapter 2. Issues in section 1.6.2.3 and 1.6.2.4 are discussed in Chapters 3 and 0 respectively. Finally EBSD issues in 1.6.2.5 are dealt in Chapter 5. Appendixes I and II introduce the work to address issues presented respectively in sections 1.6.2.6and 1.6.2.7.

1.6.2.1 Dealing with demand management options

A sustainable water resources balance can more easily be achieved through a combination of new supplies and demand management programmes (Froukh, 2001, McDonald et al., 2003). Demand management is typically a low-regret adaptation measure (both financially and environmentally) ‘given large uncertainties about future non-climate and climate pressures’ (Parker and Wilby, 2013). Even though regulators in England encourage companies to give high priority in reducing leakage and promoting efficient use of water among customers (EA et al., 2012a, Ofwat, 2009b), traditionally water management in England has been ‘supply-side dominated’ (Parker and Wilby, 2013). This also reflected in past EBSD models where demand management measures have not been included or not with sufficient detail. Below two explanatory examples:

A. The 2010 ‘Water Resources of the South East (WRSE)’ regional EBSD model does not explicitly include demand management options. Demand management schemes are only embedded into water company estimated demand, which is input data to the model. This means that the model does not explicitly estimate the cost of achieving lower consumptions through demand management schemes (such as metering, tariffs, water efficiency, and leakage reduction), nor does it evaluate their least-cost schedule implementation (optimal timing of activation).

B. Water companies usually consider a constant level of annual savings for demand management schemes. If savings profiles are included to represent the schemes’ deterioration over time, these profiles are accounted starting from the scheme’s activation, which is fixed (a model input data). For example Southern Water Company considers that water efficiency schemes have saving profiles which first increase during their 5-year implementation programme (starting from year 2009 in Figure 16) and then decrease for the remaining of the planning horizon to take account of ‘breakdowns, lack of maintenance, removal or replacements’(Southern Water, 2009). Fixing the first year implementation for demand management schemes means that the optimisation model does not have the flexibility to determine ‘when’ (which year) it is more cost-effective to implement such options.

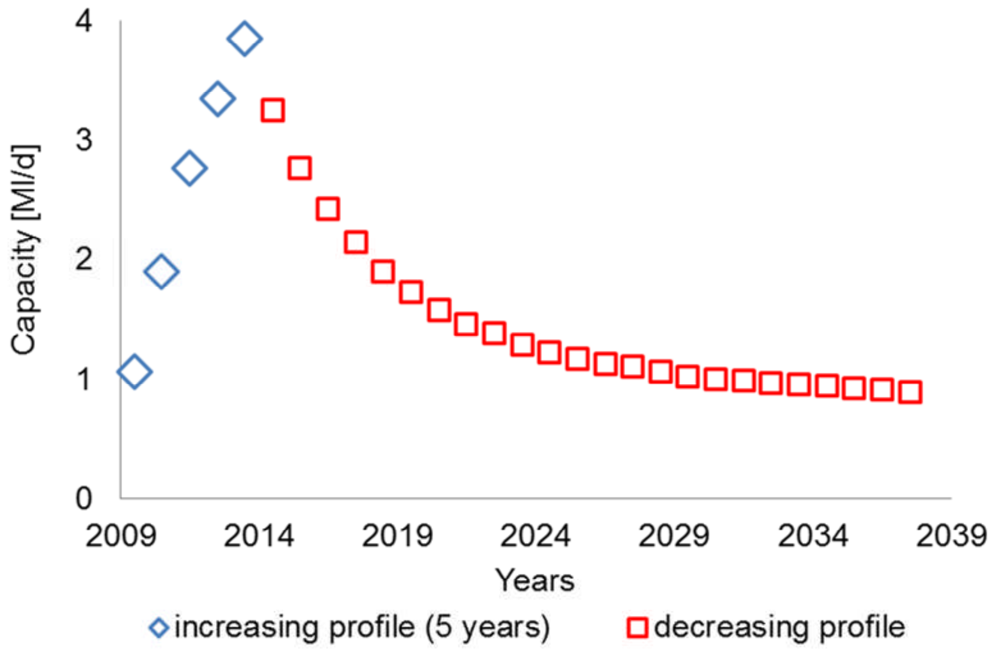

Figure 16: Company target water efficiency activity through the planning period, adopted from (Southern Water, 2009)

Previous literature work on demand management measures and their inclusion into water supply modelling is limited. Examples in include: 1. simulation models (Loukas et al., 2007, Wang et al., 2011) that don't consider scheduling (timing of activation) nor user-defined savings profiles for demand management schemes; 2. cost-effectiveness analysis (Aulong et al., 2009) which rank options based on their economic efficiency; and 3. optimisation models (Zarghami et al., 2008) where savings are calculated as a percentage of the total water supplied in the network.

Since water companies determine their own savings profiles based on experience and local information, a new EBSD model formulation should be developed that: 1. allows embedding companies' pre-defined saving profiles into the EBSD model formulation; 2. allows the optimisation model to evaluate when (which year) to implement a demand management option over the planning horizon.

1.6.2.2 Dealing with infeasibilities

When applied to real-word studies, least-cost optimisation models are frequently infeasible. Infeasibilities may arise from errors in the modelling process or because of conflicting constraints (Fiering et al., 1986). Many studies have been conducted in the literature for developing new algorithms able to detect (Obuchowska, 2012) and solve (Bockmayr and Pisaruk, 2006, Fischetti and Lodi, 2008) infeasibilities in mixed integer linear programming (MILP) problems (used in this thesis, see 1.8). Even if these methods are valuable tools for detecting infeasibilities, they have limitations when dealing with the quality of the identified feasible solution. Bockmayr and Pisaruk (2006) developed an algorithm that identifies model infeasibilities and returns a feasible solution whose quality, as the author states, strongly depends on the number of non-zero binary variables in the solution. Fischetti and Lodi (2008) adopted a two-stage process; artificial variables are first introduced to relax the model constraints and detect infeasibilities. Then, a penalty is added to the costs in the objective function. Such penalty counts the number of the violated constraints. A proper balancing of the two terms (costs and infeasibility penalty) may not be easily achieved as numerical errors may occur when mixing very large with very small numbers.

In the case of water supply planning problems, infeasibilities often arise due to: 1. limitations on existing supplies for environmental protection reasons; 2. constraints on the availability of new resources (conservation measures can be implemented quickly, whereas building a new reservoir takes several years). Below we describe two real-world case examples where infeasibilities have occurred in EBSD models:

A. In 2008 Thames Water company submitted a draft Water Resource Management Plan (WRMP) with significant deficits occurring in the London area over the 2007-2035 planning horizon. Even if deficits were starting at year 2007, the minimum date for implementing new schemes was set to year 2010, with proposed options able to cover such deficits only starting from year 2014.

B. Modelling from the 2013 WRSE project revealed infeasibilities in 7 out of the 34 demand areas included in the region (R. Critchley and D. Marshallsay, 2013)

In EBSD models, infeasibilities can be tracked with the mass balance equation, that is when the companies' available supply is lower than the forecast demand (see points A and B above). Other constraints such as upper bounds on resource usage, options availability, exclusivity or prerequisite conditions, may cause some level of infeasibility; these often represent practical, political or environmental restrictions that cannot be easily 'relaxed'. Therefore, rather than identifying the set of constraints critical to feasibility, as in the literature above, working on the mass balance equation would be advisable. In place of using an EBSD model that minimises costs under the 'supply equals demand' mass-balance condition, a new approach should be developed, able to: 1. quantify the level of infeasibility 2. return a feasible solution that satisfies 'as much demand as possible' at minimum cost. The method should avoid using a weighted objective function to prevent numerical errors from occurring and worsening the quality of the identified feasible solution.

1.6.2.3 Inter-company transfers

In a 2010 regional EBSD study (EA, 2010b) the WRSE group showed that, by only considering schemes proposed in water company resources management plans, by 2035 some water resource zones will have deficits while others will remain in surplus. This means that water resources in the South East are not equally distributed and that existing infrastructure constrain their transfer (EA, 2010b). In addition to this, the presence of regulatory penalties for not meeting expected level of service may incentivise water companies to rely on their own resources rather than imports from other companies (Severn Trent Water, 2010). Furthermore, according to the 2010-2014 regulation, if a company invests in a new resource, a return can be earned on the associated capital expenditure, while if the company imports water from an external area, the associated expenditure is classified as operating cost and no return can be earn on it. This may have refrained water companies from developing new bulk transfers (Ofwat, 2010c).

In this context, the WRSE group carried out EBSD modelling to identify new sharing opportunities within the South East of England (EA, 2005b, EA, 2010b, Padula et al., 2013, R. Critchley and D. Marshallsay, 2013). However the model’s ability to identify new inter-company transfers is limited to only considering those proposed by water companies. This may overlook transfers schemes that could contribute to a lower cost solution.

1.6.2.4 Issues with Intermediate framework implementation

EBSD models are deterministic: only one least-cost schedule of options is provided, the one that meet deficits under the worst case scenario. This means that under a broad range of plausible future supply-demand conditions, an EBSD solution may not be optimal or feasible. An improvement would be to use the ‘intermediate framework’ where uncertainties are handled using Monte Carlo simulation. The ‘intermediate framework’ consists of an iterative procedure: company target headroom values are increased every time the reliability of the EBSD model solution (frequency of system failure) is lower than a pre-defined target level of service (company chosen maximum frequency of failure).

In practice the EBSD ‘intermediate framework’, by re-evaluating companies’ headroom values, has led to some confusion which has generally discouraged its application. This is because water company target headroom estimates follow an already established regulatory guideline (UKWIR, 2002d) and therefore it is not clear by how much the target headroom values should be increased. An extension of the EBSD ‘intermediate framework’ could be developed to overcome confusion around its implementation.

1.6.2.5 Representing regulatory drivers

EBSD is applied in a regulatory context: companies in England make profits by outperforming the regulatory assumptions on the cost of capital or on operating expenditure. When deciding which option to propose in their plans a potentially significant factor is whether a company thinks it is more likely to be able to outperform the assumptions on capital expenditure or on operating costs. In the last years a preference towards capital cost intensive solutions (e.g. reservoirs) has been noted (Ofwat, 2011, Severn Trent Water, 2010) in lieu of some-times more cost-effective schemes (e.g. demand management measures or bulk transfers) that are operating expenditure based. This phenomenon is often referred to in the industry as ‘capital bias’. Reasons for the bias may be the relative strength of incentives that the regulator places on expenditure on capital assets compared to those related to day-to-day operating expenditure (Ofwat, 2011, Severn Trent Water, 2010). If there were an EBSD extension able to represent major regulatory drivers of water companies’ investment decisions this could be used as a tool to test different regulations.

1.6.2.6 Accounting for the residual costs

EBSD models in England typically consider a 25 to 30 year planning horizon within which investment decisions are made and costs are accounted for. Expenditures beyond the planning horizon are not included. ‘Residual costs’ (i.e. the proportion of the scheme’s cost to keep the scheme operational beyond the planning horizon), should be accounted to avoid biased comparison of schemes with varying economic life: capital costs intensive schemes with long economic lives may be preferred to short-term operating cost based schemes. This may happen because not all annualised capital costs may be accounted for by the model within the planning horizon. Therefore the EBSD model may consider as least-cost a capital cost-intensive scheme. Also if a scheme has a long economic life, spreading its capital cost over the entire life may return a lower cost than an operating cost-based scheme where costs are closely tied in for each year (operating costs are in k£/year, while capital costs are in k£). Recent guidelines from the Environment Agency, (EA et al., 2012a, EA et al., 2012b) request companies to account for the asset's whole life costs.

1.6.2.7 Single-objective optimisation

EBSD is a least-cost single-objective framework; it requires all aspects of system performance to be translated into costs. This can give an incomplete picture of the benefits and limitations of certain schemes which are difficult to monetise and include in the model.

There are metrics of system performance which are important for decision makers and that are not monetary such as engineering or environmental performance (Fagan et al., 2010). Technical engineering metrics can refer to the likelihood of system failure (reliability), the system rapidity to recover from a failure (resilience), or the magnitude of the system failure (vulnerability). These tangible measures can be used to demonstrate more detailed assessment of different strategies (Asefa et al., 2014, Hashimoto et al., 1982). The EBSD framework does not use such metrics. System reliability is considered but as a constraint (through the choice of a level of service at which to estimate supply yields – 'DO').

Even though EBSD model cannot quantify these and other metrics, planners often have a feel for how different schemes would perform and may have preferences regarding scheme types (e.g. prefer demand management measures over transfers, etc.). Given the uncertainty around projected scheme capital and operating costs, it could be said that the least-cost package identified by an EBSD model is in some ways arbitrary and the 'best' solution to a water resource planning problem may not coincide with this 'optimal' solution. Given the uncertainty of cost estimates and the inability of the EBSD models to embed metrics that quantify important non-monetary metrics of system performance, it would be valuable to identify a diverse (in terms of portfolio composition) set of near-optimal (close to least-cost) plans and present these to decision-makers. For example some near-optimal plans may allow decision-makers to delay or avoid the implementation of controversial assets which present technical risk or political challenges.

1.7 Research questions

Despite its limitations, EBSD is the current framework for infrastructure planning in England. Given it is likely that the EBSD approach will remain the used in the near and mid-term, this thesis asks what extensions could improve it and address some of its issues and limitations? The objective of this thesis is to apply, asses and extend the current English supply-demand water planning framework using real-world case-studies. Various mathematical programming formulations are proposed built and applied using mixed integer linear programming techniques.

Specifically, in this thesis we seek to answer the following questions:

1. Is it possible to embed in EBSD pre-defined annual saving profiles for demand management schemes? Such profiles should be accounted starting from the schemes' first year of implementation.
2. Is there an EBSD extension that can be developed to quantify network infeasibilities and return a feasible solution? The approach should not use a weighted objective function (costs plus penalty terms for infeasibilities) as this could affect the quality of the model solution.
3. Is it possible to expand the 2013 WRSE model formulation (proposed in Chapter 2) to identify new inter-company transfers in the South East region beyond the one already proposed in water company resources management plans?
4. Can the EBSD 'intermediate framework' be amended by a new iterative approach which does not require varying company headroom values to identify a 'reliable' set of schemes? Or if headroom values are varied, can a suggestion be made regarding how much these should be increased at each iteration?
5. Is it possible to develop an EBSD-based model formulation to investigate how regulation in England influences water companies' investment decisions? The model should answer the following questions: does regulation drive companies towards certain types of investments (e.g. capital-intensive schemes rather than schemes with higher operating expenditure)? If yes, what are the key regulatory drivers for such a 'bias'?
6. Is it possible to expand the EBSD model formulation to account for costs of selected options over their useful life?
7. Rather than finding a single least-cost solution, is it possible to use the EBSD model to generate a diverse set of near-optimal solutions that provide both

company decision makers and regulators with a wider range of alternatives for solving the capacity expansion problem?

This thesis answers the above questions in the following Chapters: questions 1 and 2 are addressed in Chapter 2, questions 3 in Chapter 3 and question 4 in Chapter 4. Finally Chapter 5 answers question 5, while Appendixes I and II address questions 6 and 7 respectively.

1.8 Discussion of the methodology

To address the research questions, we review below why we consider the selected research methods are appropriate.

This thesis develops and applies capacity expansion optimisation modelling approaches for large-scale regional water supply systems. The starting point is the English EBSD water supply planning framework. Merits of EBSD, that justify its application to this thesis, include: a) its applicability to large-scale networks with complex interdependences as the WRSE region, b) its institutional appropriateness: EBSD allows water companies to demonstrate their investment decisions at least economic cost, which is what regulators require, c) its suitability to capacity expansion problems: EBSD models not only define ‘what’ combination of options should be built to meet future deficits, but also provides the options’ year of activation (scheduling) over the planning horizon. The objective of this thesis is to address some EBSD issues and limitations.

1. This thesis uses optimisation techniques to support capacity expansion decisions within EBSD. If a simulation approach were used, a list of portfolios should have been pre-defined which would have been a challenging task because:

- EBSD models are applied to large-scale systems: the 2013 WRSE network contains 1065 of options, water companies’ networks can be composed up to hundreds of options.

- Even if, out of the hundreds of options, water companies identified a plausible set of portfolios, and applied simulation to select one portfolio among these, it is not possible to demonstrate that the selected portfolio is least-cost or that it does not deviate unreasonably from the least-cost solution. This is an important consideration if we consider EBSD is applied in a regulatory context: the privatised water companies in

England must demonstrate regulators their water resources management plans are ‘socially efficient and least cost’(UKWIR, 2002a, UKWIR, 2002b);

- Finding a plausible portfolio to a capacity expansion problem, not only requires identifying ‘what’ to build but also ‘when’ over a long term planning horizon. Deciding ‘when’ each combination of options must be implemented, is not an easy task as there is a trade-off to consider between the economies of scale (it is less expensive building large facilities earlier in the planning horizon rather than a sequence of smaller ones in the future) and the cost of installing capacity before it is needed (if expenditures are pushed into the future their present worth value decreases).

2. Among all optimisation methods, this thesis adopts mathematical programming techniques, specifically ‘mixed integer linear programming’ (MILP). MILP is a straightforward choice for solving EBSD models because:

- EBSD models are linear as the complex relationships among the physical and hydrological variables in the water system are estimated by water companies using external simulation models. Further nonlinearities due to the non-convex cost functions are dealt in EBSD by fixing the design capacity and costs of proposed schemes: for optional schemes few discrete possible capacity and costs values are proposed (each occurring in a separate node of the EBSD model network – see Chapter 2). Dealing with discrete schemes rather than continuous cost curves leads to sub-optimal solutions as the ‘real’ solution to the problem likely lays between two discretised options. However this limitation is mitigated by the fact that companies and regulators are often unwilling or unable to generate continuous cost curves reliably;

- Linear optimisation techniques have the advantage to guarantee convergence to a global optimum solution. Since EBSD models are used by water companies in England to demonstrate regulators their plans are ‘socially efficient and least-cost’ (UKWIR, 2002a, UKWIR, 2002b), being able to guarantee global optimality or the vicinity to optimality (see near-optimal solutions in paragraph 1.4.2 and Appendix II) is important.

- Capacity expansion formulations within MILP do not need to be custom-coded but can be solved using the ‘off-the-shelf’ generalised software and solvers which reduces the complexity of solving, maintaining and improving such models.

1.9 Summary of Thesis structure and research contributions

This section outlines the main contributions of each Chapter.

The introduction lays the foundation for the report. The research problem and the research issues are introduced to justify the scope of this thesis. The methodology is described by summarising the modelling techniques available in the literature for solving capacity expansion problems, with a particular focus on water resources systems. The research methods were introduced and their appropriateness to the specific research problem was justified.

In Chapter 2 an EBSD deterministic capacity expansion optimisation model is formulated and applied to the WRSE regional water supply system. This model was developed for and used by the actual 'Water Resources in the South East' (WRSE) stakeholder group. User-defined annual water saving profiles are allowed for demand management schemes. These profiles are accounted starting from the option's first year of activation. A two-step optimisation approach is introduced to prevent the infeasibilities that inevitably appear in real applications. The approach does not use a weighted objective function (because real schemes' costs are added up to penalty costs for flow injected at infeasible water resource zones) where numerical errors may arise by mixing very large and small numbers. Multiple water demand scenarios are considered simultaneously to ensure the supply-demand balance is preserved across different demand conditions and that variable costs are accurately assessed. A wide range of supplementary constraints are also formulated to consider the interdependencies between schemes (pre-requisite, mutual exclusivity, etc.).

In Chapter 3 the model formulation of Chapter 2 is expanded to evaluate the benefits from a fully interconnected regional system. The model is applied to the WRSE area: in addition to companies' proposed transfers, inter-company transfers are allowed to connect neighbouring demand areas in surplus, with those in deficits. The capital expenditure for the additional inter-company transfers is calculated using a non-convex cost curve estimated by Ofwat, the economic regulator, in a recent study. The non-convex cost curve is approximated through a piecewise linear function.

In Chapter 4 the EBSD 'intermediate framework' (referred to as '*THR-strategy*') is implemented and compared with a new iterative procedure referred to as 'CUT-strategy'. The '*CUT-strategy*' identifies a 'reliable' schedule of options to a supply-demand balance problem without having to modify company target headroom values.

This overcomes the uncertainty around upgrading companies' target headroom values which has often prevented the 'intermediate framework' from being applied in practice. Both the '*CUT-strategy*' and the '*THR-strategy*' use Monte Carlo simulation to identify the level of service (probability of failure) of the solution set identified by the deterministic EBSD model. If the level of service is lower than the company's target level of service, than under the '*CUT-strategy*' new constraints are added at the next run of the EBSD model to avoid this solution (schedule of options) from being selected again in the next run of the EBSD model. This procedure is repeated many times until a combination of options is found whose level of service is equal or higher than the target level of service.

Chapter 5 introduces an EBSD modified capacity expansion formulation. The new formulation is built to analyse the incentives offered to regulated water utility monopolies by regulatory constraints on their rate of return and maximum prices. The model is applied to the case of price control in England adopted for the 2010-2014 period. Particular emphasis is placed on understanding how regulation influences water company investment decisions such as their desire to engage in transfers with neighbouring companies. The model finds the schedule of new schemes that maintains the annual supply-demand balance and maximise companies' profit under the 2010-2014 price control process. The profit-maximising investment solution is then compared with the least-cost solution (social optimum); differences in the two sets of results leads to a discussion.

Appendix I presents an extension to the EBSD model formulation that accommodates recent Environment Agency guidelines (EA et al., 2012a) which require companies to consider costs over the whole assets useful lives. In Appendix II multiple supply-demand schedules are generated for the WRSE network which are 'sufficiently close' to the one identified by the fully deterministic version of the EBSD model ('current framework'). It is argued that exploring a diverse set of nearly optimal solutions is more appropriate than only considering the single least-cost solution or the optimum under a few scenarios. The generated set of nearly optimal solutions are displayed in parallel axis plots to show their diversity in terms of frequency of selection, extent of use, and timing of activation. Results show that near-optimal plans within a few percentages from the global optimal solution present a high diversity in terms of schemes' selection and extent of use. For example a 6% more expensive near-optimal plan is found that uses reservoirs at a 24% higher extent and transfer options at a 30% lower extent.

Parallel axis plots can also be used to identify schemes that represent low-regret decisions (if the scheme appears in most near-optimal solutions) or to investigate whether it is possible to delay the implementation of some problematic investments (e.g. a reservoir causing landscape or heritage issues).

Chapter 2

LEAST ECONOMIC COST REGIONAL WATER SUPPLY PLANNING

2 Introduction

In this Chapter, the EBSD capacity expansion model is developed. The proposed model poses the capacity expansion problem in a form easily tractable by a mathematical program by boiling the problem down to a supply-demand balance per water resource zone. Such 'water resource zones' (WRZ) aggregate interconnected supply areas where residents face the same likelihood of supply shortfalls. User-defined annual water saving profiles for demand management (water conservation) schemes are enabled. Multiple water demand scenarios are considered simultaneously to ensure the supply-demand balance is preserved across high demand conditions and that operating costs are accurately assessed. A wide range of supplementary constraints are formulated to consider the interdependencies between schemes (pre-requisite, mutual exclusivity, etc.). Finally, a two-step optimisation process is introduced to prevent the infeasibilities that inevitably appear in real applications.

The Chapter is structured as follows: section 2.1 shows the model formulation, section 2.2 describes the water planning context in England and Wales as well as the model application to a regional system composed of six water companies. Section 2.3 introduces the branch and bound algorithm adopted to solve the optimisation problems presented in this Chapter and in later ones. Section 2.4 shows the model's results. Discussion of results is presented in section 2.5 followed by the conclusions in section 2.6.

2.1 Model Formulation

2.1.1 Nomenclature

Indices of Sets

i,j	nodes (source, junction, demand)
t	time periods (years)

θ	generic time index
scen	demand scenarios

<u>*Sets*</u>

I	set of nodes
T	set of time periods (years) $T=\{t : t \text{ is any year} \wedge 1 \leq t \leq tmax=25\}$
Θ	set of generic time periods $\Theta=\{\theta : \theta \text{ is a generic time index} \wedge 1 \leq \theta \leq \theta max=25\}$
SCEN	set identifying the demand scenarios
EXDO	set of existing sources
OPTSOU	set of optional nodes; these include supply-side schemes and demand management schemes
DM	set of new demand management schemes
SUPPLYN	set of all existing and optional supply schemes (i.e. includes sets *EXDO* and *OPTSOU*)
DEM	set of demand nodes
LEX	set of existing links
LFT	set of new links/transfers
LINK	set of all existing and optional links (i.e. includes sets *LEX* and *LFT*)
CONN	network connectivity

<u>*Parameters*</u>

$afccs_i$	annualised capital costs for new nodes
$afccl_{i,j}$	annualised capital costs for new links
$sfix_i$	fixed annual costs for new nodes
$lfix_{i,j}$	fixed annual costs for new nodes
$carbs_{i,t}$	annual capital carbon costs emissions for optional sources
$carbl_{i,j,t}$	annual capital carbon costs emissions for optional links
$offs_i$	one-off fixed financial operating costs for demand management schemes
$vopexs_{i,t}$	variable costs incurred at nodes
$vopexl_{i,j,t}$	variable costs incurred at links
$svar_{i,t}$	unit variable costs incurred at nodes
$lvar_{i,j,t}$	unit variable costs incurred at links

$sr_{i,t,scen}$ reductions in deployable output applied to each demand node *i*, during year t and scenario *scen*

$di_{i,t,scen}$ distribution input applied to each demand node *i*, during year *t* and scenario *scen*

$thr_{i,t,scen}$ target headroom applied to each demand node *i*, during year *t* and scenario *scen*

$smin_i/smax_i$ minimum/maximum supply from source *i* during year *t*

$lmin_{i,j}/lmax_{i,j}$ minimum/maximum supply from link *i,j* during year *t*

$sav_{i,\theta,scen}$ maximum saving from a demand management option i during year t and scenario scen

dm_aval_i first year of availability for demand management schemes

first_yr first year of the planning horizon

$tscen_{scen}$ average annual scenario duration in number of weeks.

penalty_cost cost to inject flows flow at infeasible WRZs (infeasibility flow procedure)

dr discount rate

Binary Variables

$AS_{i,t}$ 1 if source *i* is active during year *t*, 0 otherwise.

$AL_{i,j,t}$ 1 if link *i,j* is active during year *t*, 0 otherwise.

$FS_{i,t}$ 1 at first year *t* of activation of selected schemes *i*, 0 otherwise.

Positive Variables

$S_{i,t,scen}$ supply from source *i* at year *t* and scenario *scen* to meet demand plus target headroom

$Q_{i,j,t,scen}$ supply from source *i* at year *t* and scenario *scen* to meet demand plus target headroom

$Sut_{i,t,scen}$ supply from source *i* at year *t* and scenario *scen* to meet demand

$Qut_{i,j,t,scen}$ supply from source *i* at year *t* and scenario *scen* to meet demand

$\alpha_{i,t,scen}$ demand satisfaction level for node *i* at year *t* and scenario *scen*.

$INFEAS\_FLOW_{i,t,scen}$ fictitious flow that can be injected to infeasible WRZs

2.1.2 Basic model formulation

A minimum cost capacity expansion optimisation model formulation for water supply systems is described which can be solved by off-the-shelf mixed integer linear program (MILP) solvers. The model identifies the least discounted economic cost annual schedule of capacity expansions to maintain the system's supply-demand balance over a T-year planning horizon.

The model makes two kinds of decisions: the extent of annual use of supply and demand management options (for both existing and optional schemes) and annual investment decisions on optional schemes. The model has a network structure: water demand nodes (Water Resource Zones, WRZs) are connected to supply and demand management options within their WRZ, or to other demand nodes (to represent transfers). To represent supply schemes that can be shared between more than one WRZ, 'source-junction' nodes are used to connect supply options to the demand nodes.

The model is formulated as a mixed integer linear programming (MILP) optimisation problem. A single objective is used: minimisation of discounted capital, fixed and variable costs (Equation2.1). Inclusion of carbon, social and environmental economic costs means the model can be considered an economic-engineering tool (Lund et al., 2006) rather than an engineering (financial cost minimising) model. One-off financial costs are also included. These incur just once over the planning period, when an option is selected.

$$min \sum_{t=1}^{tmax} \frac{1}{(1+dr)^{t-1}} \left\{ \begin{array}{l} \sum\limits_{i \in SUPPLYN} \left[\begin{array}{l} \left(afccs_i + sfix_i + carbs_{i,t} \right) \times AS_{i,t} \\ + \left(off_i \times FS_{i,t} \right) + vopexs_{i,t} \end{array} \right] \\ + \sum\limits_{(i,j) \in CON} \left[\begin{array}{l} \left(afccl_{i,j} + carbl_{i,j,t} + lfix_{i,j} \right) \times AL_{i,j,t} \\ + vopexl_{i,j,t} \end{array} \right] \end{array} \right\} \tag{2.1}$$

In the equation above *dr* is the discount rate, *tmax* the final year of the planning period, *CON* is a set which defines the connections among nodes *i, j* in the network, *SUPPLYN* is the set of all supply nodes (both existing sources *EXDO* and optional schemes *OPTSOU*). A discount factor equal to $1/(1+dr)^t$ assumes all costs are incurred at the year-end. $afccs_i$, $afccl_{i,j}$ are respectively the sum of annualised capital expenditures (capital financial, capital environmental and social costs) for optional schemes (*OPTSOU*) and companies' proposed optional links (*LFT*), while $sfix_i$ and $lfix_{i,j}$ are respectively the fixed annual costs (operating, carbon, environmental and social) for optional nodes and links. $vopexs_{i,t}$ and $vopexl_{i,j,t}$ are variable costs (operating, carbon, environmental and social) incurred at nodes and links respectively. Finally $carbs_{i,t}$ and $carbl_{i,j,t}$ are user-defined annual profiles of capital carbon costs for optional sources and links respectively, while off_i are one-off costs applied to demand management options.

One-off costs include fixed financial, social, environmental and carbon emission related costs.

Environmental costs reflect the environmental impact that an option might have, whereas social costs are measured as a loss of consumer surplus (UKWIR, 2002a, UKWIR, 2002b). Carbon costs are related to the option emissions of carbon dioxide. To estimate carbon costs of the options projected emissions, water companies use the latest government guidance on the cost of carbon (Climate Change Economics and Dpt. of Energy and Climate Change, 2009). $S_{i,t}$ and $Q_{i,j,t}$ are non-negative decision variables defining the extent of annual use of supply for sources and links respectively. $AS_{i,t}$ and $AL_{i,j,t}$ are binary decision variables that activate new supply options i and new links (i, j) when they change from 0 to 1 during any particular year. $FS_{i,t}$ are binary variables equal to one at the first year of activation of an optional node (*OPTSOU*) or optional link (*LFT*) respectively and equal to zero otherwise. $FS_{i,t}$ is defined by equations below:

$$FS_{i,t} = \left(AS_{i,t} - AS_{i,t-1} \right) \quad \forall i \in OPTSOU, t \in T \qquad 2.2$$

In equation 2.2 above T is the set of time periods (years). All decision variables are in volume/time except for binary variables which represent yes/no activation decisions. In this Chapter decision variables (binary and continuous) and set declarations are in upper caseletters; parameters (input data) are in lower case.

Variable costs $vopexs_{i,t}$ and $vopexl_{i,j,t}$ are calculated multiplying unit variable costs ($svar_{i,t}$ for sources and $lvar_{i,j,t}$ for links) by the continuous usage decision variables $S_{i,t}$ and Capital costs can be included as a custom time-series of cash outflows or using simple cash flow methods (see the following section 2.1.3). All costs are in real and not nominal terms to avoid having toforecast inflation (P. Belli et al., 2002).

The objective function equation is subject to a 'mass balance' constraint at all nodes of the network (Equation 2.3) and to capacity constraints at nodes and links (Equations 2.4 to 2.7):

$$S_{i,t}\big|_{i \in SUPPLYN} - sr_{i,t}\big|_{i \in EXDO} + \sum_{j:(j,i) \in CON} Q_{j,i,t} - \sum_{j:(i,j) \in CON} Q_{i,j,t} = di_{i,t}\big|_{i \in DEM} + thr_{i,t}\big|_{i \in DEM} \qquad 2.3$$
$$\forall i \in I, t \in T$$

$$smin_{i,t} \times AS_{i,t} \le S_{i,t} \le smax_{i,t} \times AS_{i,t} \qquad \forall i \in OPTSOU, t \in T \qquad 2.4$$

$$smin_{i,t} \le S_{i,t} \le smax_{i,t} \qquad \forall i \in EXDO, t \in T \qquad 2.5$$

$$lmin_{i,j,t} \times AL_{i,j,t} \le Q_{i,j,t} \le lmax_{i,j,t} \times AL_{i,j,t} \quad \forall (i,j) \in LFT, t \in T \qquad 2.6$$

$$lmin_{i,j,t} \le Q_{i,j,t} \le lmax_{i,j,t} \quad \forall (i,j) \in LEX, t \in T \qquad 2.7$$

In the equations above *DEM* is the set of demand nodes (WRZs), *LEX* is the set of all existing links. $\Sigma_j Q_{i,j,t}$ is the sum of the flows entering node i during year t, $\Sigma_j Q_{i,j,t}$ is the sum of the flows leaving node i during year t. $smin_{i,t}$, $smax_{i,t}$ are respectively the minimum and maximum capacities for schemes (*EXDO* and *OPTSOU*), while $lmin_{i,j,t}$ and $lmax_{i,j,t}$ are respectively the minimum and maximum capacities for links. Binary variables $AS_{i,t}$, $AL_{i,j,t}$ are applied only to optional sources and links.

In equation 2.3 $sr_{i,t}$ is the outage while $di_{i,t}$ and $thr_{i,t}$ are respectively the distribution input (DI) and target headroom (THR). Terms $di_{i,t}$ and $thr_{i,t}$ are applied at WRZ level. Outage is defined as a temporary short-term loss in deployable output (EA et al., 2012a, EA et al., 2012b) while the DI is the amount of treated water entering the distribution system. THR is a margin of spare resource between forecast demand and water available for use, used to take account of uncertainty around supply and demand estimates (UKWIR, 2002c). Process losses and reduction in the firm yield might be added in the equation above to increase the WRZ distribution input when either one are greater than zero. Process losses are defined as the summation of both raw and treatment work losses and operational use (EA et al., 2012a, EA et al., 2012b). Reduction of deployable output may include factors such as sustainability reduction (i.e. reduction in deployable output required by the EA to meet statutory and/or environmental requirements) and impact of climate change (EA et al., 2012a). Sustainability reductions can be either a fixed value or a proportion of annual use.

2.1.3 Calculation of annualised costs

Annualised financial costs ($afccs_i$ for nodes i, $afccl_{i,j}$ for links i,j) are calculated in the following way. Financial costs include: capital investments, environmental and social costs for optional sources (both supply-side and demand management schemes) and new links. Undiscounted financial costs for optional sources and links ($caps_i$ for nodes i, $capl_{i,j}$ for links i,j) are spread over the construction period of the assets (cps_i for supply-side nodes and demand management measures and $cpl_{i,j}$ for links). This provides annual cash flows whose future value is then evaluated at the end of the construction period:

$$fccs_i = \sum_{tt=0}^{cps-1} \frac{caps_i}{cps_i} \times (1+ic)^{tt} \quad \forall i \in OPTSOU \tag{2.8}$$

$$fccl_{i,j} = \sum_{tt=0}^{cpl-1} \frac{capl_{i,j}}{cpl_{i,j}} \times (1+ic)^{tt} \quad \forall (i,j) \in LFT \tag{2.9}$$

In the equations above ic is the interest rate and tt is an annual time index for the construction period. Future capital costs are then annualised using:

$$afccs_i = fccs_i \times \frac{ic(1+ic)^{ns_i}}{(1+ic)^{ns_i} - 1} \quad \forall i \in OPTSOU \tag{2.10}$$

$$afccl_{i,j} = fccl_{i,j} \times \frac{ic(1+ic)^{nl_{i,j}}}{(1+ic)^{nl_{i,j}} - 1} \quad \forall (i,j) \in LFT \tag{2.11}$$

where ns_i is the asset lifetime of for supply schemes i, while $nl_{i,j}$ is the asset life of link i,j. The equations above imply the model only considers annualised costs during the planning horizon and does not consider capital costs to be incurred beyond the planning horizon.

2.1.4 Multiple demand scenario formulation

Supplies must meet demand in relatively infrequent periods of high demand when costs are typically higher. This implies the above model will over-estimate costs under normal conditions. To prevent this multiple simultaneous water demand scenarios are introduced in a single model run. For example four demand scenarios (identified by set SCEN) are considered in our application: dry year annual average, dry year critical period, minimum deployable output and normal year annual average. Supplies must meet the most stringent scenario but variable costs are considered and weighted according to how frequently each demand scenario is expected. Solving n demand scenarios requires n sets of continuous decision variables (in place of one set for $S_{i,t}$ and $Q_{i,j,t}$) to describe how much each scheme (supply, demand management or transfer) is used annually under each scenario.

2.1.4.1 Mass balance and capacity constraints under multiple water demand scenarios

Two sets of mass balance equations are introduced: the first (Equation 2.13) to make sure that the selected infrastructure is able to meet the most stringent scenario (demand is equal to DI plus THR), the second (Equation 2.14) to evaluate variable costs based on schemes actual utilisation rather than as if peak demands were maintained all year long (THR is set equal to zero). Each mass balance equation has a different set of annual use variables ($S_{i,t,scen}$, $Q_{i,j,t,scen}$ in Equation 2.13 and $Sut_{i,t,scen}$, $Qut_{i,j,t,scen}$ in Equation 2.14). Setting THR to zero means that the required annual use variables ($Qut_{i,j,t,scen}$, $Sut_{i,t,scen}$) will be lower thus incurring less variable costs. This ensures estimated variable costs will reflect how much schemes are likely to be used over the 25 year period. This second set of use variables ($Qut_{i,j,t,scen}$, $Sut_{i,t,scen}$) is the one that appears in the weighted variable costs terms included in the objective function equation.

$$\begin{aligned}&S_{i,t,scen}\big|_{i\in SUPPLYN} - sr_{i,t,scen}\big|_{i\in EXDO} + \sum_{j:(j,i)\in CON} Q_{j,i,t,scen}\\ &- \sum_{j:(i,j)\in CON} Q_{i,j,t,scen} = di_{i,t,scen}\big|_{i\in DEM} + thr_{i,t,scen}\big|_{i\in DEM}\\ &\forall i\in I, t\in T, scen\in SCEN\end{aligned} \quad 2.12$$

$$\begin{aligned}&Sut_{i,t,scen}\big|_{i\in SUPPLYN} - sr_{i,t,scen}\big|_{i\in EXDO} \sum_{j:(j,i)\in CON} Qut_{j,i,t,scen}\\ &- \sum_{j:(i,j)\in CON} Qut_{i,j,t,scen} = di_{i,t,scen}\big|_{i\in DEM}\\ &\forall i\in I, t\in T, scen\in SCEN\end{aligned} \quad 2.13$$

Equations above are applied to each node of the network (supply nodes, junctions, demand nodes and supply junctions) and also apply to multiple demand scenarios *scen* and each year *t* of the planning horizon. *SCEN* is the set of all demand scenarios. Annual use variables for links ($Q_{i,j,t,scen}$, $Qut_{i,j,t,scen}$) and nodes ($S_{i,t,scen}$, $Sut_{i,t,scen}$) also appear in capacity constraints equations 2.4 to 2.7 (in place of variables $Q_{i,j,t}$ and $S_{i,t}$) where the minimum and maximum capacities ($smin_{i,t,scen}$, $smax_{i,t,scen}$, $lmin_{i,j,t,scen}$, $lmax_{i,j,t,scen}$) are now defined over set *SCEN*. Terms $sr_{i,t,scen}$, $di_{i,t,scen}$ and $thr_{i,t,scen}$ are respectively the outage allowance, distribution input and the target level of service during year *t*, scenario *scen* and for demand node *i*.

2.1.4.2 Objective function

The objective function is identical to Equation 2.1 with the difference that now variable costs are weighted over four scenarios (set *SCEN*). One set of capital costs and fixed operating costs and four sets of variable costs are used. Variable costs are evaluated using $Qut_{i,j,t,scen}$ and $Sut_{i,t,scen}$ variables. If *scen* are the elements of set *SCEN* and $tscen_{scen}$ is the weight for each demand scenario (e.g. in number of weeks per year), then the weighted average is expressed by Equation 2.14 (for nodes) and Equation 2.15 (for links):

$$vopexs_{i,t} = \frac{\sum_{scen \in SCEN} tscen_{scen} \times svar_i \times Sut_{i,t,scen}}{\sum_{scen \in SCEN} tscen_{scen}} \quad \forall i \in SUPPLYN, t \in T \tag{2.14}$$

$$vopexl_{i,j,t} = \frac{\sum_{scen \in SCEN} tscen_{scen} \times lvar_{i,j} \times Qut_{i,j,t,scen}}{\sum_{scen \in SCEN} tscen_{scen}} \quad \forall (i,j) \in LINKS, t \in T \tag{2.15}$$

where *LINKS* is the set of existing (*LEX*) and optional (*LFT*) transfers, while $svar_i$, $lvar_{i,j}$ and $vopexs_{i,t}$, $vopexl_{i,j,t}$ are respectively the variable costs in pence/m^3 and the weighted average variable costs incurred at nodes and links. Scenario durations ($tscen_{scen}$) are weights estimated based on expected occurrence with no dimension. Unit variable costs on existing links (*LEX*) can be used to encourage the model to use WRZs own existing deployable output (local sources) before importing from other WRZs.

2.1.5 Additional constraints

Other constraints have been added to describe interdependences between options in the water supply network representing practical, technological, social and/or environmental policies and restrictions. These include: ‘mutually exclusive’ constraints which apply when only one supply or link from a set of alternatives should be implemented, ‘prerequisite AND’ constraints that assure a link/source form group A is implemented only if all links/sources from group B have been activated, ‘prerequisite OR’ constraints that assure a link/source form group A is implemented only if at least one option (link or source) from a set B of prerequisite schemes has been activated, ‘prerequisite with LAG TIME’ constraints that allow a scheme to be activated only a certain number of years after the activation of another prerequisite scheme (node or link), ‘dependency’ constraints that force a node or link to be activated at the same time as another group of optional schemes are implemented. ‘Capacity connectivity constraints’ force the total supply (Ml/d) from a group of schemes in set A to be lower than the total supply from selected schemes in set B, plus an allowance which may vary depending on the scenario (set *SCEN*).

‘Ratchet’ constraints can be used to impose a monotonically increasing usage of schemes to avoid constructing schemes that are used only for few years or regularly used below their maximum capacity. Ratchet constraints are a good example of a policy or ‘political’ constraint. ‘Consistent use constraints’ (also referred to as ‘capacity constraints’) are used to discourage the discontinuous use of future supply sources by forcing the binary variables of optional schemes and links to be one after their first year of activation). Finally, start date constraints limit the first use of any link or supply scheme and represent the time it takes to construct and receive benefits from the options. The detailed formulation for these constraints is reported below.

2.1.5.1 Ratchet Constraints

Ratchet constraints can be used to impose a monotonically (consistently) increasing usage of links and supply schemes during the planning horizon. They are usually implemented to discourage the use of an option during only a part of the planning period. This constraint is rarely used except when requested for strategic reasons.

$$S_{i,t+1,scen} \geq S_{i,t,scen} \quad \forall scen \in SCEN, i \in SRC, t < tmax - 1 \qquad 2.16$$

$$Q_{i,j,t+1,scen} \geq Q_{i,j,t,scen} \quad \forall scen \in SCEN, (i,j) \in LRC, t < tmax - 1 \qquad 2.17$$

In the equations above *SRC* and *IRC* are subsets used to identify those nodes and links that are subject to ratchet constraints.

2.1.5.2 Start Date Constraints

Some of the optional nodes and links can be available only after a certain year $\eta \in T$:

$$AS_{i,t} = 0 \quad \forall i \in OPTSOU, t < \eta \qquad 2.18$$

$$AL_{i,j,t} = 0 \quad \forall (i,j) \in LFT, t < \eta \qquad 2.19$$

2.1.5.3 Continuity Constraints

Continuity or irreversibility constraints maintain the activation of binary variables ($AS_{i,t}$ $AL_{i,j,t}$) at a value of one once a scheme is selected as most schemes cannot be un-built later on to save costs.

$$AS_{i,t+1} \geq AS_{i,t} \quad \forall i \in OPTSOU, t \leq (tmax - 1) \qquad 2.20$$

$$AL_{i,j,t+1} \geq AL_{i,j,t} \quad \forall (i,j) \in LFT, t \leq (tmax - 1) \qquad 2.21$$

2.1.5.4 Mutually Exclusive Constraints

'Mutually exclusive' constraints apply when only one supply node or link can be implemented from a set of optional nodes *z* selected from set *I* and (*i*,*j*) links selected from set *CON*.

If *MUT_SET* is as a set composed by the mutually exclusive equations (*MUT_SET* = {*eq* : *eq* is an equation}), this constraint can be written as:

$$\sum_{z} AS_{z,t} + \sum_{i,j} AL_{i,j,t} \leq 1 \qquad \forall t \in T, eq \in MUT\_SET \tag{2.22}$$

With $z \in I$ and $(z,eq) \in M\_EXCL$, while links $(i,j) \in CON$ and $(i,j,eq) \in N\_EXCL$. *M_EXCL* is a subset of the Cartesian product between a subset of nodes *z* belonging to set *I* and set *MUT_SET*, while *N_EXCL* is a subset of the Cartesian product between a subset of links (*i*,*j*) belonging to set *CON* and set *MUT_SET*. *i*, *j*, *z* are node indices and are used to refer to different nodes that belong to the same set *I*.

2.1.5.5 Prerequisite Constraints (AND Condition)

Prerequisite constraints (AND condition) assure that an optional source $z^* \in I$ (or link $(i,j) \in CON$) is allowed to be implemented only if a full set of prerequisite nodes a selected from set *I* and links (*b*,*c*) selected from set *CON* has already been activated.

If *PRERSET_AND* is the set composed by the prerequisite equations (*PRERSET_AND* ={*eq* : *eq* is an equation}), then this constraints can be written as:

$$AS_{z^*,t} \leq \frac{\sum_{a} AS_{a,t} + \sum_{b,c} AL_{b,c,t}}{num\_Nright_{eq} + num\_Lright_{eq}} \qquad \forall t \in T, eq \in PRERSET\_AND \tag{2.23}$$

$$AL_{(i,j)^*,t} \leq \frac{\sum_{a} AS_{a,t} + \sum_{b,c} AL_{b,c,t}}{num\_Nright_{eq} + num\_Lright_{eq}} \qquad \forall t \in T, eq \in PRERSET\_AND \tag{2.24}$$

with $a \in I$ and $(a,eq) \in P\_AND$, while $(b,c) \in CON$ and $(b,c,eq) \in N\_AND$. *P_AND* is a subset of the Cartesian product between a subset of nodes a belonging to set *I* and set

PRERSET_AND, while *N_AND* is a subset of the Cartesian product between a specific subset of links (i,j) belonging to set *CON* and set *PRERSET_AND*. Node *z** and link *(i,j)** change with the equation *eq*. Num_Nright_{eq} and Num_Lright_{eq} are the total number of elements (nodes and links respectively) contained in sets *P_AND* and *N_AND*.

2.1.5.6 Prerequisite Constraints (OR Condition)

This constraint is used if the activation of at least one node a selected from set *I*, or link (*b,c*) selected from set *CON* is sufficient for the activation of node *z** in year *t* (equation C10) or link (*i,j*)* in year *t* (equation 2.26).

If *PRERSET_OR* is the set composed by the prerequisite (OR condition) equations (*PRERSET_OR* = {*eq* : *eq* is an equation}), then the constraints can be written as:

$$AS_{z^*,t} \le \sum_a AS_{a,t} + \sum_{b,c} AL_{b,c,t} \qquad \forall t \in T, eq \in PRERSET\_OR \tag{2.25}$$

$$AL_{(i,j)^*,t} \le \sum_a AS_{a,t} + \sum_{b,c} AL_{b,c,t} \qquad \forall t \in T, eq \in PRERSET\_OR \tag{2.26}$$

with $a \in I$ and $(a,eq) \in P\_OR$, while $(b,c) \in CON$ and $(b,c,eq) \in N\_OR$. *P_OR* is a subset of the Cartesian product between a subset of nodes a belonging to set *I* and set *PRERSET_OR*, while *N_OR* is a subset of the Cartesian product between a subset of links (*i,j*) belonging to set *CON* and set *PRERSET_OR*. Node *z** and links *(i,j)** change with the equation *eq*.

To help understand these equations, consider a first constraint (*eq1*) with node '*opt1*' that cannot be activated if one or more among the following options has already been activated: node '*opt2*', node '*opt3*' and link '*WRZ1.WRZ3*'. Equation 2.25 becomes:

$$AS_{'opt1',t} \le AS_{'opt2',t} + AS_{'opt3',t} + AL_{'WRZ1','WRZ3',t} \quad \forall t, eq_1$$

With *P_OR* = {(*opt2,eq1*), (*opt3,eq1*)} and *N_OR* = {(*WRZ1,WRZ2,eq1*)}.

2.1.5.7 Prerequisite Constraints with LAG TIME

With this constraint a supply scheme *z** is allowed to be activated at least δ years after the activation of another node *a** selected from set *I*. If *PRESET_LAG* is the set composed by the prerequisite with LAG time equations (*PRESET_LAG* = {*eq* : *eq* is an equation}), then this constraint can be written as:

$$AS_{z^*,t} = 0 \qquad \forall\, t \le \delta \tag{2.27}$$

$$AS_{z^*,t} \le AS_{a^*,t-\delta} \qquad \forall\, t \le \delta \tag{2.28}$$

where node z^* and node a^* change with the equation *eq*.

2.1.5.8 Mutually Dependent Constraints

These constraints force a specific node z^* or link $(i,j)^*$ to be activated at the same time as a group of optional nodes a selected from set *I* and optional links *(b,c)* selected from set *CON*. If *DEPENDENT* is a set composed of the mutually dependent equations (*DEPENDENT* ={*eq* : *eq* is an equation}), then the dependency constraint can be written as:

$$AS_{z^*,t} = \frac{\sum_a AS_{a,t} + \sum_{b,c} AL_{b,c,t}}{num\_Nright_{eq} + num\_Lright_{eq}} \quad \forall t \in T, eq \in DEPENDENT \tag{2.29}$$

If applied to links the mutually dependent constraint becomes:

$$AL_{(i,j)^*,t} = \frac{\sum_a AS_{a,t} + \sum_{b,c} AL_{b,c,t}}{num\_Nright_{eq} + num\_Lright_{eq}} \quad \forall t \in T, eq \in DEPENDENT \tag{2.30}$$

with $a \in I$ and $(a,eq) \in P\_DEP$ while $(b,c) \in CON$ and $(b,c,eq) \in N\ DEP$. *P_DEP* is a subset of the Cartesian product between a subset of nodes a belonging to set *I* and set *DEPENDENT*, while *N_DEP* is a subset of the Cartesian product between a subset of links (*i*,*j*) belonging to set *CON* and set *DEPENDENT*. Node z^* and link $(i,j)^*$ change withthe equations *equation*

2.1.5.9 Capacity Connectivity Constraints

These constraints force supply (in Ml/d) from a set of selected nodes z and links *i*, *j* to be less than total supply provided by other selected nodes *a* and links (*i*, *j*), plus an allowance (*flow_par*) which may vary depending on the scenario (set *SCEN*). If *CAPACITY* is a set composed by the capacity connectivity equations, then these constraints can be written as:

$$\sum_{z} S_{z,t,scen} + \sum_{i,j} Q_{i,j,t,scen} =$$

$$\left[\sum_{a} S_{a,t,scen} + \sum_{b,c} Q_{b,c,t,scen} \right] + flow\_par_{eq,scen} \qquad 2.31$$

$$\forall t \in T, scen \in SCEN, eq \in CAPACITY$$

with $z \in I$ and $(z, eq) \in M\_CAP$, $(i,j) \in CON$ and $(i,j,eq) \in Q\_CAP$, $a \in I$ and $(a,eq) \in P\_CAP$, while $(b,c) \in CON$ and $(b,c,eq) \in N\_CAP$. *M_CAP* is a subset of the Cartesian product between a subset of nodes *z* belonging to set *I* and set *CAPACITY*, *Q_CAP* is a subset of the Cartesian product between specific links (i,j) belonging to set *CON* and set *CAPACITY*, *P_CAP* is a subset of the Cartesian product between a subset of nodes a belonging to set *I* and set *CAPACITY, and N_CAP* is a subset of the Cartesian product between a specific subset of links (b,c) belonging to set *CON* and set *CAPACITY*.

2.1.6 Demand management option constraints

Demand management options have user-defined annual water saving profiles which begin from their first year of activation. When the first year of activation is a decision to be optimised, a new continuous variable ($W_{t,dm}$) has to be introduced:

$$W_{i,t} \geq AS_{i,t} - AS_{i,t-1} \quad \forall t \in T, i \in DM \qquad 2.32$$

$$\sum_{t} W_{t,i} \leq 1 \quad \forall t \in T, i \in DM \qquad 2.33$$

Equation 2.32 ensures variable $W_{i,t}$ is greater than (or equal to) one in the first year of activation and greater than (or equal to) zero the years thereafter. Equation 2.33 (together with Equation 2.32) forces $W_{i,t}$ to be equal to 1 (if the demand management option is selected) at the first year of activation. If the first year of activation (year t^*) must be fixed, equation 2.32 above can be replaced fixing $W_{i,t^*} = 1$.

If θ is a generic set containing as many elements as the number of years included in the planning horizon, then the capacity constraints are given by equation 2.34.

$$S_{i,t,scen} = \sum_{\theta=0}^{T-1} sav_{i,\theta,scen} * W_{i,t-\theta} \qquad \forall t \in T, i \in DM, scen \in SCEN \qquad 2.34$$

Equation 2.34 ensures the annual ‘supply’ is accounted from the first year of activation of the demand management scheme. Unlike supply schemes that can be used in any given year less than maximum capacity (Equations 2.4 to 2.7), from demand management options scheme contributions are fixed to the scheme's forecasted ability to reduce demand ($sav_{i,\theta,scen}$, see Equation 2.34). This means that, for selected demand management options, the extent of annual use variable $S_{i,t,scen}$ has to assume the same value to the one as variable $Sut_{i,t,scen}$. This is ensured through the following constraint:

$$S_{i,t,scen} = Sut_{i,t,scen} \qquad \forall i \in DM, t \in T, scen \in SCEN \tag{2.35}$$

2.1.7 Dealing with model infeasibilities

Mathematical infeasibilities can arise when the sum of all available supply and demand management schemes cannot meet the demand of one or more WRZs in one or more years. Two strategies are available to deal with network infeasibilities: 1) infeasibility flows, where strongly penalised flows can be injected at WRZ demand nodes during any year to allow feasibility, and 2) demand reductions, where demands are reduced just enough to ensure all WRZ supply-demand balances are feasible in each year. Although method 1 is frequently adopted in network optimisation, defining high unit ('penalty') costs for the infeasibility flows can make the model less sensitive to the real scheme costs and lead to sub-optimal results. Method 2 was therefore adopted in this project.

2.1.7.1 Infeasibility flow procedure

If this method is implemented the mass balance constraint previously defined by Equation 2.12 is modified into Equation 2.36. The same modifications must be applied to mass balance Equation 2.13.

$$\begin{aligned}
&INFEAS_FLOW_{i,t,scen}\big|_{i \in DEM} + S_{i,t,scen}\big|_{i \in SUPPLYN} \\
&-sr_{i,t,scen}\big|_{i \in EXDO} + \sum_{j:(j,i)\in CON} Q_{j,i,t,scen} - \sum_{j:(i,j)\in CON} Q_{i,j,t,scen} \\
&= di_{i,t,scen}\big|_{i \in DEM} + thr_{i,t,scen}\big|_{i \in DEM} \\
&\forall i \in I, t \in T, scen \in SCEN
\end{aligned} \tag{2.36}$$

In the equation above $INFEAS\_FLOW_{i,t,scen}$ is a continuous positive variable representing flows (fictitious supply in volume per year) that can be injected at the WRZ level (set *DEM*) during each year t and scenario scen. These flows have high (`penalty') costs to ensure they are used only in case the network is infeasible (the existing and proposed supply-side and demand-side options are insufficient to meet future demands). The objective function Equation 2.1 now becomes:

$$min \sum_{t=1}^{tmax} \left\{ \frac{1}{(1+dr)^{t-1}} \begin{bmatrix} \sum_{i} \left(afccs_i + sfix_i\right) \times AS_{i,t} + \left(carbs_{i,t} + off_i\right) \times FS_{i,t} + vopexs_{i,t} \\ + \sum_{i,j} \left(afccl_{i,j} + lfix_{i,j}\right) \times AL_{i,j,t} + \left(carbl_{i,j,t}\right) \times FL_{i,j,t} + vopexl_{i,j,t} \end{bmatrix} + \left[penalty\_cost \times \sum_{scen \in SCEN} \sum_{i \in DEM} INFEAS\_FLOW_{i,t,scen} \right] \right\} \qquad 2.37$$

A limitation of this method is the definition of the unit cost *penalty_cost*. If this is too low, infeasible flows may be chosen over available optional schemes (*OPTSOU*), if it is too high the objective function value (Equation 2.37) may become so large that the model becomes less sensitive to the real scheme costs and therefore produces suboptimal results. This issue led to develop and use the procedure described below.

2.1.7.2 Demand reduction procedure

The demand reduction procedure deals with infeasibilities in the WRSE network through a 2-step process: 1. reduce demands in WRZs in years with an infeasible balance just enough to make those balances feasible, 2. run the feasible model with reduced demands.

Step 1: Solve the following problem:

$$max \sum_{scen \in SCEN} \sum_{i \in DEM} \sum_{t \in T} \alpha_{i,t,scen} \qquad 2.38$$

Subject to all constraint equations listed in the previous sections with the additional condition that $0 \leq \alpha_{i,t,scen} \leq 1$. Mass balance equations 2.12and 2.13 are now written as:

$$\begin{aligned} & S_{i,t,scen}\big|_{i \in SUPPLYN} - sr_{i,t,scen}\big|_{i \in EXDO} \\ & + \sum_{j:(j,i) \in CON} Q_{j,i,t,scen} - \sum_{j:(i,j) \in CON} Q_{i,j,t,scen} \\ & = \alpha_{i,t,scen}\big|_{i \in DEM} \times \left(di_{i,t,scen}\big|_{i \in DEM} + thr_{i,t,scen}\big|_{i \in DEM}\right) \\ & \forall i \in I, t \in T, scen \in SCEN \end{aligned} \qquad 2.39$$

$$\begin{aligned} & S_{i,t,scen}\big|_{i \in SUPPLYN} - sr_{i,t,scen}\big|_{i \in EXDO} + \sum_{j:(j,i) \in CON} Q_{j,i,t,scen} \\ & - \sum_{j:(i,j) \in CON} Q_{i,j,t,scen} = \alpha_{i,t,scen}\big|_{i \in DEM} \times di_{i,t,scen}\big|_{i \in DEM} \\ & \forall i \in I, t \in T, scen \in SCEN \end{aligned} \qquad 2.40$$

Step 2: Fix $\alpha_{i,t,scen}$ values obtained from step 1 and solve the model using Equation 2.1 as objective function, equations 2.39 and 2.40for mass balances and all other constraints described in previous paragraphs. In the equations above, $\alpha_{i,t,scen}$ is a continuous positive variable defined for all demand scenarios.

2.2 Application: Planning South East England's Water Supply

2.2.1 Case study water resource system

The proposed capacity expansion optimisation model is applied to a regional system composed of 34 water resource zones (WRZs), managed by the 6 water companies in South East England that serve a 17.6 million population (R. Critchley and D. Marshallsay, 2013). Input data for the model (demands by water resource zone, all costs, capacities of existing and optional schemes, outage, process losses, sustainability reductions and climate change allowances) are provided by the water companies for each water resource zone.

Process losses, reductions of deployable output, target headroom and water demand are aggregated at a water resource zone level. Four demand scenarios are here included: dry year annual average (DYAA), normal year annual average (NYAA), dry year critical period (DYCP) and minimum deployable output (MDO) period (see Chapter 1, section 1.5.1).

Links between water resource zones are either existing or optional. Optional links represent new transfers between water resource zones or the prolonging of existing agreements. When optional transfers start from areas not in the modelled network they are represented as new supply nodes (TR nodes).

Besides water demand nodes (representing WRZs) and junctions, network nodes are either existing or optional supply sources. Optional nodes are divided into supply-side schemes and demand management demand management schemes. These schemes include water efficiency, leakage and metering.

Supply-side schemes represented as nodes include reservoirs (RES), groundwater utilisation schemes (GW), surface water abstraction (SW), effluent reuse schemes (ER), desalination (DESAL), water treatment works (WTW), aquifer storage and recharge schemes (ASR), and other options ('other') such as conjunctive use schemes, network constraints removal or network improvements.

Some major supply schemes have several discrete capacities and cost values included as separate mutually exclusive nodes. For example, reservoir options in the Upper Thames area are proposed in different sizes which can be built in one phase or in two separate phases (e.g. 50 Mm^3 in phase 1+ 50 Mm^3 in phase 2). In some cases the phase 2 option can only be implemented a pre-defined number of years after the phase 1 option is selected (pre-requisite constraint with lag time).

Demand management options have water company defined annual water saving profiles which start from their first year of activation. Leakage reduction options include pressure management with new pressure release valves, district metering area data analysis for targeted repairs or network improvements, and reconfiguration as well as other strategies such as new detection technologies. Pro-actively fixing leaks before they are reported is referred to as active leakage control. These options have diminishing returns as their level of implementation increases. To gauge the extent to which ALC should be implemented, companies consider ‘tranches’ (bundles) of implementation. Each tranche is represented in the model with different prerequisite options (e.g. ‘tranch2’ can only be implemented after ‘tranch1’). Successive tranches have diminishing returns: water available for use is the same but capital and operating costs increase.

Metering options include ‘change of occupier’ instalments, metering on left over domestic or commercial properties (e.g. difficult to fit), targeted compulsory metering, community integrated metering (new meters and upgrade of existing ones), metering of all household within stressed areas and programmes to achieve pre-defined level of meter installations by a specific year. Metering options also include seasonal tariff and rising block tariff. Tariff is exclusive to ‘change of occupier’ schemes and metering schemes for household within stressed areas.

Water efficiency measures include a range of different measures: household and commercial water audit, supply or retrofit of efficient devices (water butts, low flow taps, low use washing machine), rainwater harvesting and grey water reuse schemes.

The proposed model is applied to two different networks: Case 1 and Case 2. In Case 1 only supply-side options are included whereas Case 2 includes both new supplies and demand management schemes (water conservation). Both models use the same least economic cost objective function, demand reduction feasibility assurance scheme (see paragraph 2.1.7.2), mass balance constraints (equations 2.12 and 2.13) and scheme interdependence constraints (see sections 2.1.5.4 to 2.1.5.9). The 272 interdependence constraints used in the model (in both cases) include mutual exclusivity (103 constraints), pre-requisites (‘and’ 91 of which 1 with ‘lag time’, ‘or’ 4- see Appendix C for definitions of the constraint subtypes), mutual dependency (68 constraints) and 6 ‘capacity connectivity’ constraints.

2.3 Optimisation modelling system

All implementations in this thesis are done within the GAMS modelling system (Brooke A et al., 2010), using the CPLEX (ILOG, 2007) solver for mixed integer linear programming (MILP) problems. A modelling system consists of a language compiler used to encode the model formulation stated by the user (objective function and constraints) and to transfer it to commercial integrated grade solvers. Solvers are software that implement optimisation algorithms to solve the user-defined system of equations. The CPLEX solver uses a ‘branch and bound’ algorithm (B&B) to solve MILP problems. Below the B&B algorithm is introduced together with the notion of GAP (stopping criteria for the B&B algorithm), a concept that appears later on in this Chapter.

To explain how the B&B algorithm works, the example in Table 17 is used (Thomas F. Edgar et al., 2001). In Table 17, y_1, y_2 and y_3 are binary variables. The first step of the B&B algorithm (node 1 in Table 17) consists of ‘relaxing’ the binary variables so that they can assume any fractional value between zero and one. If in the solution y_1, y_2 and y_3 have integer values, the B&B algorithm has solved the MILP problem, and f in Table 17 is the optimal value of the objective function. If instead one or more variables have fractional values (see y_2 in Table 17), the B&B selects one of the fractional variables and creates a fork with two new ‘relaxed’ sub-problems (node 2 and 3 in Table 17). The selected variable is then set equal to zero in one node (in node 2, Table 17) and equal to one in the other one (node 3, Table 17). The process of creating two relaxed sub-problems is called ‘branching’. Branching rules has been widely studied (Wolsey L. A. and Nemhauser G. L., 1988). If the model finds a feasible integer solution in one of the two nodes, the B&B algorithm does not ‘branch’ further from it and the node is said to be ‘fathomed’ (see node 2, Table 17). The algorithm stops its search when a ‘measure of optimality’ is guaranteed. The optimality criterion compares the best integer solution found during the search (BI, referred to as ‘incumbent’) against the best ‘relaxed’ solution within the B&B search tree not yet fully explored (BF). This difference is called the GAP. The B&B algorithm terminates its search if the GAP = (BI-BF) is equal to or lower than some fraction *tol* of the incumbent's objective value. Specifically, when the following relation holds: GAP/(1-|BF|)≤*tol*, the BI is considered to be the global optimum within the desired tolerance. The ratio GAP/(1-|BF|) is referred to in this thesis as 'relative GAP' or RGAP. The factor '1' ensures the ratio GAP/(1-|BF|) makes sense when BI is equal to zero. A maximum tolerance of 0.1 is usually considered (Yeomans and Huang, 2003).

In the example of Table 17, integer solutions are only identified in node 2 and node 4. Since Table 17 refers to a maximisation problem, the 'incumbent' solution is the one in node 2 (the value of the objective function *f* in node 4 is equal to 44, and is lower than in node 2). The BF solution is reached in node 1 (*f* in node is higher than in nodes 3 and 5). The relative gap is therefore equal to [(129-126)/(1+126)]=0.024.

CPLEX uses the branch and bound algorithm and applies 'cutting planes', i.e., constraints that reduce the feasible region of the linear programming relaxation without eliminating any feasible solutions for the MILP problem. The combination of B&B and cutting planes form the 'branch and cut' algorithm (Padberg and Rinaldi, 1991). Combining cutting planes with B&B provides a more efficient approach to solve large-scale MILP problems (Lieberman, 2004).

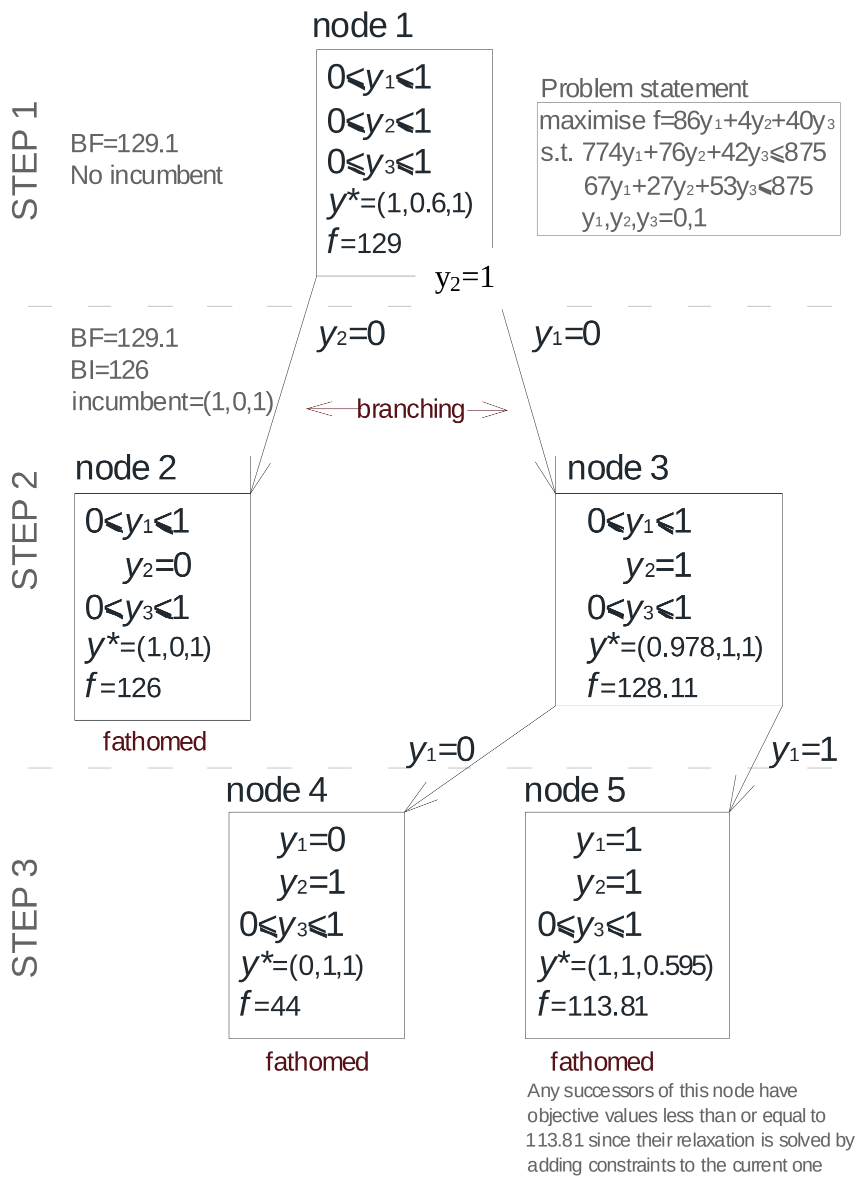

Figure 17: The branch and bound algorithm from (Thomas F. Edgar et al., 2001).

2.4 Model results

The model is solved over a 25 year planning period (2015-2039) with a 4.5 % discount rate (Ofwat, 2009b) for Case 1 (only supply-side options) and Case 2 (supply and demand management options) and four demand scenarios (dry year annual average DYAA, dry year critical period DYCP, minimum deployable output MDO and normal year annual average NYAA). The mixed integer linear programming model is implemented in GAMS (Brooke A et al., 2010) and solved using the CPLEX solver. Table 3 gives model dimensions for Case 1 and Case 2. The models were run using two computers in a Windows XP environment, i.e. a DELL 2.6 GHz machine with 16 GB RAM, and a DELL Precision T7500 2.4 GHz with 24 GB RAM.

	Model statistics	
	Case 1	Case 2
Tot number of variables	487,551	623,376
Binary variables	26,366	59,150

Table 3: Model statistics for Case 1 (with no demand management schemes) and Case 2 (with demand management schemes).

Both models provide in output the year of activation of optional supply-side options, demand management measures and transfers schemes, together with their optimal annual use levels under each demand scenario. There are no demand management schemes in Case 1. Case 1 model converges to a 2.76% relative GAP on a 16 GB RAM machine, over a thirty hours run (see Figure 20), while Case 2 model reached a 5.94% relative gap in 46 hours (see Figure 20) on a DELL Precision T7500 machine.

Figure 18 shows the evolution of the upper and lower bound solutions identified by CPLEX for both Case 1 and Case 2. Total costs (associated to both existing and optional assets) are equal to £M 1048 for Case1 and £M 980 for Case 2, meaning that the implementation of the demand management schemes allows a total saving of £M 68.

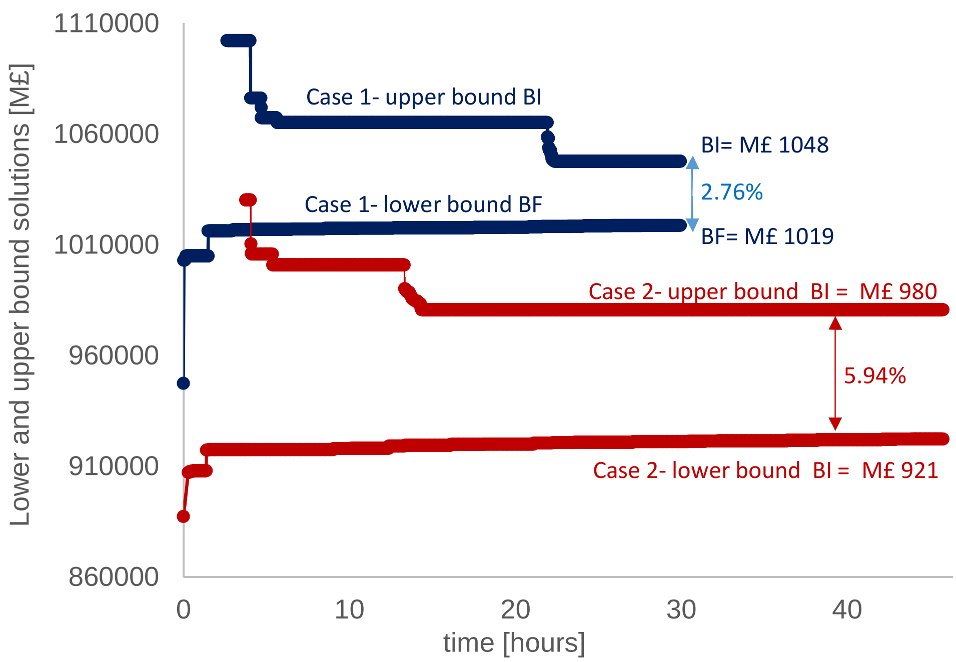

Figure 18: Evolution over time of the upper and lower bound solutions for Case 1 and Case 2 runs. Costs derive from both existing and optional schemes.

Table 4 shows the cost of activated optional schemes grouped by type. Costs are split into capital expenditure, fixed operating costs, one-off costs for water efficiency measures, and variable operating costs. Variable operating costs are weighted over the four demand scenarios. The total capital expenditure on optional assets decreases from

£M 672 in Case 1 solution to £M 611 in Case 2 (Table 4); fixed operating costs decrease from £M 65 to £M 53, while variable operating costs from £M 151 to £M 98.

	Costs [£M]							
	Case 1				Case 2			
	Capital	Fixed operating	Weighted variable operating	One-off	Capital costs	Fixed operating	Weighted variable operating	One-off
Supply options	562	36	139	/	363	20	94	/
MET	-	-	-	/	19	3	-5	/
LEAK	-	-	-	/	141	10	-1	/
WEFF	-	-	-	/	0	0	-1	83
LFT	165	42	4	/	87	20	12	/
Total	***672***	***65***	***151***	***/***	***611***	***53***	***98***	***83***

Table 4: Total discounted costs over 25-year time horizon for Case 1 and Case 2 for transfers, supply-des options and demand management measures.

Effluent reuse schemes provide the 34% and the 27% of total capital expenditure in Case 1 and Case 2, respectively. These schemes also generate the 69% and 74% of weighted variable costs in Case 1 and Case 2, respectively (Table 5).

Effluent re-use schemes consist of using treated wastewater as a source of potable water. There are two types of effluent reuse schemes: direct and indirect. The first one consists of using recycled and treated wastewater and is only adopted in the UK for non-potable applications (industry and irrigation (EA, 2011). The second one consists of discharging treated water in a watercourse or reservoir. The discharged water is then abstracted and treated again to reach potable standards. This allows for increased dilution, higher residence time and for the settlement of potential contaminants (EA, 2011). Effluent reuse schemes can be implemented to reduce the need for further resource development; however, there may be issues related to their implementation, such as the environmental impact of wastewater discharge and public health perception (recycled water is perceived to be less clean than water from other sources). Carbon and greenhouse gas emission are also relatively higher than those related to other supply-side schemes (EA, 2011); this is due to the reverse osmosis process, an energy intensive process often used to treat wastewater for re-use.

Company proposed transfers (set LFT) provide the 16% and 14% of total capital costs under Case 1 and Case 2 respectively (Table 4). In Case 1, the activation of a reservoir scheme generates £M 48 discounted capital costs. This is equivalent to the 72% of total capital costs on reservoir options (see Table 5). This scheme is no longer activated in Case 2 leading to a significant cost reduction (from £M 68 to £M 11, Table 5).

	Costs [£M]					
	Case 1			Case 2		
	Capital	Fixed operating	Weighted variable operating	Capital	Fixed operating + One-off	Weighted variable operating
ASR	27	4	5	7	1	1
DESAL	7	0.4	0.1	8	1	0
ER	227	12	103	167	8	73
GW	135	11	13	94	7	8
Other	2	0.5	0.4	2	0.5	0.4
RES	68	-3	3	11	-1	1
SW	9	-4	2	13	-7	1
WTW	50	3	8	47	3	7
MET	/	/	/	19	3	-5
LEAK	/	/	/	142	10	-1
WEFF	/	/	/	-	82	-1
TR	39	12	4	15	8	2
LFT	109	29	13	87	20	12
TOTAL	***672***	***65***	***151***	***611***	***136***	***98***

Table 5: Discounted costs for activated links demand management measures and supply-side options aggregated by option type for both Case 1 and Case 2 networks. Columns may not add up due to rounding.

The Case 2 solution is dominated by smaller options including demand management measures, such as leakage control, metering schemes and water efficiency measures. Amongst all of the demand management schemes, leakage reduction schemes have the highest extent of use (see Table 6). These schemes contribute to the 23% of total capital expenditure on optional schemes (see Table 5).

The activation of demand management schemes in Case 2, reduces costs on groundwater and effluent reuse options; specifically the capital expenditure on effluent reuse schemes is £M 227 in Case 1 and £M 167 in Case 2, while the one related to groundwater schemes is £M 135 in Case 1 and £M 94 in Case 2. Weighted variable costs decrease by 35% (i.e. from £M 151 in Case1 to £M98 in Case 2, Table 5). This is mainly due to the lower use/activation of effluent reuse schemes (variable operating costs on effluent reuse schemes decrease from £M 103 in Case 1 to £M 73, Table 5) and to the negative carbon costs associated to the demand management options. Negative carbon costs represent savings in greenhouse gas emissions due to the capability of demand management options to reduce water demands and the subsequent need for additional supply-side schemes.

Table 6 gives a summary of the total optimal capacity provided by selected schemes for Case 1 and 2. Leakage reduction and supply-side options contribute most significantly to the supply-demand balance. Specifically, leakage reduction schemes provide 2346 Ml/d under all demand scenarios. This corresponds to the 19% of total supply from optional schemes for the dry year critical period scenario, and the 34% for the normal year annual average scenario. Amongst all supply schemes, effluent reuse schemes provide the highest volume of supply; and specifically, a maximum of 39% of total supply in Case 1 and 60% in Case 2 (see the year annual average scenario in Table 6).

	Optimal extent of use [Ml/d]							
	Case 1				Case 2			
	DYAA	DYCP	MDO	NYAA	DYAA	DYCP	MDO	NYAA
MET	/	/	/	/	190	190	190	190
LEAK	/	/	/	/	2346	2346	2346	2346
WEFF	/	/	/	/	204	204	204	204
Total demand management	***/***	***/***	***/***	***/***	***2758***	***2758***	***2758***	***2758***
ASR	210	691	150	147	49	273	44	42
DESAL	20	108	38	/	24	118	63	7
ER	4657	4787	4721	4365	3465	3689	3576	3156
GW	1412	2264	1401	1006	1067	1681	1028	663
Other	192	217	196	184	194	218	190	180
RES	383	522	396	207	253	316	272	69
SW	1114	1466	1110	65	1110	1604	1109	54
WTW	1586	1907	1594	747	1555	1935	1518	594
TR	1207	1426	1244	531	1008	1202	1016	528
Total supply-side schemes	***10782***	***13388***	***10851***	***7252***	***8724***	***11035***	***8816***	***5294***
Supply-side+ demand management	***10782***	***13388***	***10851***	***7252***	***11483***	***13794***	***11575***	***8052***
EXDO	128409	146900	122721	124284	127759	146603	122006	123484
Total optional+ existing schemes	***139191***	***160288***	***133572***	***131536***	***139241***	***160397***	***133580***	***131536***

Table 6: Total least-cost quantity in Ml/d for activated supply-side schemes and demand management measures for Case 1 and Case 2.

The total level of supply provided by both existing and optional schemes is higher under Case 2 than Case 1 (see last row in Table 6). This is because deficits in Case 2 are lower than in Case 1 (see Table 7); Case 1 network has fewer options to meet projected demands and available schemes are often limited by ‘starting date’ constraints. Table 7 shows the magnitude (in Ml/d) of deficits in water resource zones where they occur for Case 1 and Case 2 and under the four demand scenarios. There are no deficits under the normal year annual average scenario where demand levels are lower.

	Deficit [Ml/d]					
	Case 1			Case 2		
	DYAA	DYCP	MDO	DYAA	DYCP	MDO
WRZ17	-	-	0.9	-	-	0.2
WRZ13	4.5	3	58	2.5	1.3	52.4
WRZ02	-	2.4	-	-	1.3	-
WRZ01C	10.3	27.4	-	5.2	23	-
WRZ34	-	5	-	/	/	/
WRZ22	43	97.5	-	/	/	/
WRZ18	-	-	0.8	/	/	/
WRZ03	-	-	1	/	/	/
TOTAL	***58***	***135***	***61***	***7***	***26***	***52***

Table 7: Supply-demand deficits [Ml/d] where they appear for some of the water resource zones in the network. Deficits under the normal year annual average scenario are zero.

Table 8 and Table 9 show, respectively, costs and optimal capacities for selected effluent reuse schemes. The 64% of supply (Table 9) and the 65% of capital expenditure (Table 8) on effluent reuse schemes is generated by option ‘ER_1080’. This is activated in the London water resource zone (‘WRZ22’), the one with the highest deficit in the whole network. ‘ER_1080’ is an indirect potable reuse scheme with a maximum annual capacity of 150 Ml/d. It consists of a new wastewater reuse plant that uses a reverse osmosis membrane treatment, and of a twenty-three kilometre long pipeline to discharge treated water into a river for subsequent re-abstraction. The implementation of this option may create issues concerning its environmental impact. For example, the pipeline route may affect cultural heritage resources. Significant issues in relation to gas emissions and air quality may also incur. Options ER _1074’, ‘ER _1068’, ‘ER _1070’ and ‘ER_786’ are also indirect effluent-reuse schemes.

	Costs [£M]						
	Case 1				Case 2		
Option Name	WRZ name	Capital	Fixed operating	Weighted variable operating	Capital	Fixed operating	Weighted variable operating
ER _786	WRZ06	15	1.2	1	20	1.6	1.6
ER _1080	WRZ22	147	4.3	74	127	4	63
ER _1074	WRZ22	11	1.8	5	1.3	0.2	0.6
ER _1068	WRZ22	36	3.7	15	19	2	8
ER _1070	WRZ22	18	1.2	8	/	/	/
TOTAL		***227***	***12***	***103***	***167***	***8***	***73***

Table 8: Discounted costs of selected effluent reuse schemes under ‘Case 1_maxEXDO’ and ‘Case 2_maxEXDO’ runs. Numbers may not add up due to rounding.

	Capacity [Ml/d]							
	Case 1				Case 2			
	DYAA	DYCP	MDO	NYAA	DYAA	DYCP	MDO	NYAA
ER_786	292	422	356	/	310	534	423	1.2
ER_1080	3000	3000	3000	3000	2700	2700	2698	2700
ER_1074	245	245	245	245	35	35	35	35
ER_1068	400	400	400	400	420	420	420	420
ER_1070	720	720	720	720	/	/	/	/
TOTAL	***4657***	***4787***	***4721***	***4365***	***3465***	***3689***	***3576***	***3156***

Table 9: Total extent of use of effluent reuse schemes selected in Case 1 and Case 2 runs. Numbers may not add up due to rounding.

54 water company proposed links (LFT) are activated in Case 1 and 62 in Case 2, out of 215 available ones. Table 10 shows the total supply that circulates through the selected links for each demand scenario.

	LFT optimal extent of use [Ml/d]	
	Case 1	Case 2
DYAA	3762	3154
DYCP	5168	4363
MDO	4148	3437
NYAA	2893	2726

Table 10: Total optimal extent of use of LFT schemes over the four demand scenarios and for Case 1 and Case 2 runs.

Figure 19 shows the activated optional links for both Case 1 (top panel ‘a’) and Case 2 (bottom panel ‘b’).

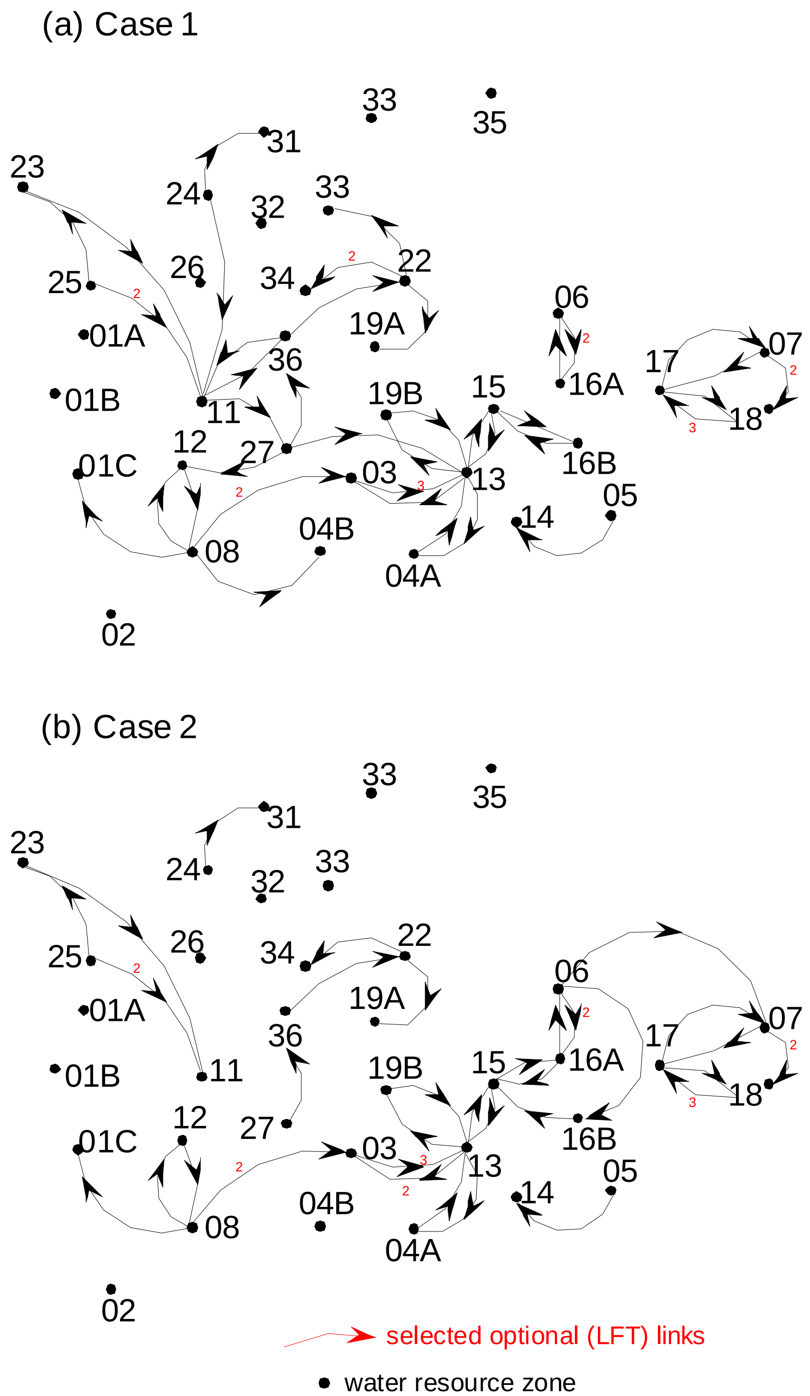

Figure 19: Links activated in Case 1 and Case 2. Numbers in red indicate the number of selected links in a specific direction. When numbers are omitted, only one link is selected.

2.4.1 Sensitivity runs on effluent reuse schemes

Sensitivity analysis was conducted to examine how the model solution would change if some of most cost-expensive effluent reuse schemes in the network (see Table 11) were disabled for both Case 1 ('Case1_noER' model) and Case 2 ('Case2_noER' model).

	Costs			
Option name	Capital [£M]	Fixed operating [£M/year]	Weighted variable operating [£M/m^3]	Max annual capacity [Ml/d]
ER_1077	123	0.4	0.03	150
ER_851	117	0.7	0.02	150
ER_1080	116	0.3	0.01	150
ER_1071	115	0.8	0.02	150
ER_1077	123	0.4	0.03	150
ER_1076	87	0.3	0.03	100
ER_849	83	0.5	0.02	100
ER_1079	81	0.3	0.01	100
ER_1070	81	0.8	0.02	100
ER_848	79	0.8	0.01	60
ER_1068	75	0.2	0.09	60
ER_1900	71	0.6	0.01	50
ER_1078	71	0.1	0.08	50
ER_1075	68	0.2	0.02	50
ER_1069	69	0.2	0.01	50

Table 11: Undiscounted costs and capacity of available effluent reuse schemes in the London water resource zone 'WRZ22'.

Figure 20 shows the evolution, over time, of the upper and lower bound solutions for both 'Case 1_noER' and 'Case 2_noER'. By excluding the effluent reuse options in Table 11, the cost of the solution increases by £M 389 for 'Case 1_noER' (from £M 1048 in Case 1 to £M 1437) and by £M 82 for 'Case 2_noER' (from £M 980 in Case 2 to £M 1062). 'Case2_noER' model reaches a 4.4% relative gap in less than 20 hours, 'Case1_noER' reaches a 2.9% relative gap in about 16 hours.

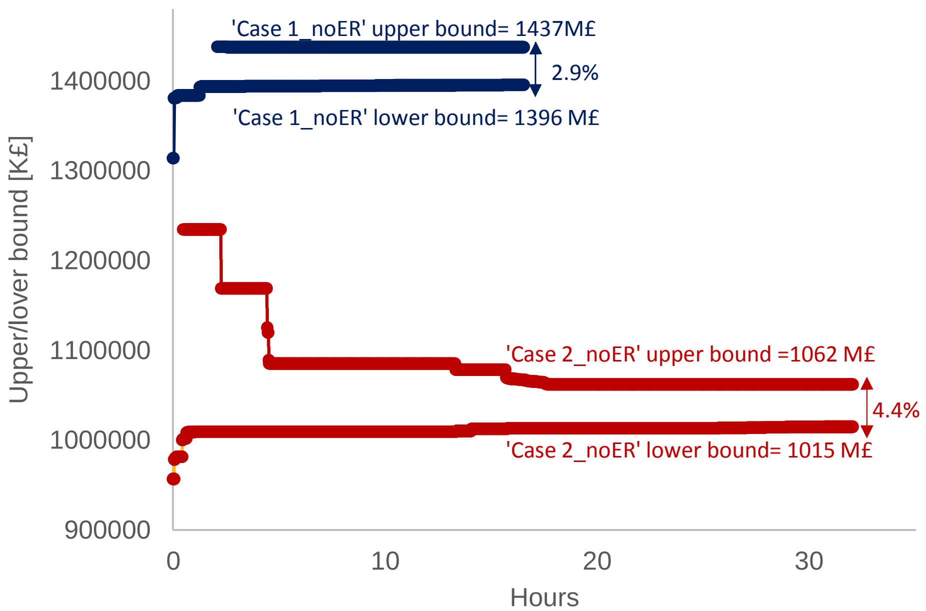

Figure 20: Evolution over time of the upper and lower bound solutions for Case 1_noER and Case 2_noER runs. Costs derives from both existing and optional schemes.

Costs of activated schemes (grouped by type) are shown in Table 12 for model 'Case1_noER' and 'Case2_noER'.

	Costs [£M]					
	'Case 1_noER'			'Case 2_noER'		
	Capital	Fixed operating	Weighted variable	Capital	Fixed Operating+ One-off	Weighted variable
ASR	46	5	10	39	3	9
DESAL	376	19	26	13	1	1
ER	22	2	3	15	1	1
GW	134	11	15	94	6	10
Other	2	0	0	2	0	0
RES	71	-4	4	32	-1	2
SW	61	26	13	62	21	16
WTW	47	3	8	47	3	7
TR	90	14	8	55	13	4
Total Supply-side schemes	***849***	***76***	***87***	***359***	***47***	***50***
MET	/	/	/	/	/	/
LEAK	/	/	/	200	9	-1
WEFF	/	/	/	-	78	-0.5
Total demand management	***/***	***/***	***/***	***200***	***87***	***-1.5***
LFT	118	28	12	85	23	11
TOTAL	***967***	***105***	***99***	***643***	***157***	***60***

Table 12: Costs of activated schemes grouped by type, for both 'Case 1_noER' and 'Case2_noER' runs

The capital expenditure increases from £M 611 in Case 2 (Table 5) to £M 643 in 'Case 2_noER' (Table 12). Fixed operating costs also increase from £M 136 in Case 2 to £M 157 in 'Case 2_noER'.

Under the dry year annual average scenario, supply from effluent reuse schemes decreases by 4216 Ml/d in 'Case 1_noER', and 3284 Ml/d in 'Case 2_noER' (Table 6 and Table 13). Contrarily, supply increases by 324 Ml/d for aquifer storage and recharge schemes, 212 Ml/d for reservoirs, 1570 Ml/d for surface water options and 483 Ml/d for imports from external areas (compare Table 6 with Table 13).

	Capacity [Ml/d]							
	'Case 1_noER'				'Case 2_noER'			
	DYAA	DYCP	MDO	NYAA	DYAA	DYCP	MDO	NYAA
MET	/	/	/	/	/	/	/	/
LEAK	/	/	/	/	2894	2894	2894	2894
WEFF	/	/	/	/	167	167	167	167
Total demand management	***/***	***/***	***/***	***/***	***3061***	***3061***	***3061***	***3061***
ASR	421	850	379	357	356	597	355	353
DESAL	1939	2028	1797	694	69	140	104	14
ER	387	571	468	22	269	405	345	/
GW	1443	2252	1450	1121	1170	1647	1163	743
Other	201	226	193	186	194	218	190	178
RES	364	447	386	287	445	528	463	180
SW	2124	3108	1615	70	2146	3174	1549	33
WTW	1569	1900	1565	715	1528	1948	1491	681
TR	1553	1635	1527	72	1428	1685	1476	502
Total supply-side schemes	***10001***	***13016***	***9379***	***4174***	***7606***	***10342***	***7135***	***2685***
Supply-side + demand management	***10001***	***13016***	***9379***	***4174***	***10667***	***13403***	***10196***	***5871***
EXDO	129190	147271	124193	127362	128575	146993	123385	125665
Total optional+ Existing schemes	***139191***	***160288***	***133572***	***131536***	***139241***	***160397***	***133580***	***131536***

Table 13: Total capacity provided by the activated schemes and grouped by type, for both 'Case 1_noER' and 'Case2_noER' runs. Existing nodes are referred to as *EXDO*.

Total supply from optional schemes decreases compared to the Case 1 and Case 2, while the one from the existing nodes increases by the same amount (compare Table 6 and Table 13). Existing schemes provide over of the 90% of the total supply (Table 6 and Table 13). These are aggregated into one node per water resource zone and have unit variable costs associated (the optimal level of variable costs on existing schemes is equal to £M 217 in 'Case 1_noER' and £M 285 in 'Case 2_noER').

2.4.2 Removing the variable costs for the existing nodes

In order to understand how costs on the existing schemes influence their optimal extent and the activation of the optional schemes, two further runs were executed. Specifically, unit variable costs on the existing schemes were set equal to zero for both Case 1 (model 'Case1_maxEXDO') and Case 2 ('Case2_maxEXDO').

	Costs [£M]					
	‘Case 1_maxEXDO’			‘Case 2_maxEXDO’		
	Capital	Fixed operating	Weighted variable	Capital	Fixed operating+ One-off	Weighted variable operating
ASR	31	4	2	16	2.2	0.4
DESAL	7	0	1	6	0.3	0.3
ER	219	12	27	153	5.5	15
GW	137	11	6	95	6.5	3.9
Other	2	0.5	0.2	2	0.4	0.3
RES	69	-2	3	13	-0.1	1.3
SW	11	-5	2	33	7.8	4.9
WTW	49	3	2	50	3.4	2.4
TR	42	14	3	14	8.5	1.3
Total optional supply-side schemes	***568***	***38***	***44***	***383***	***34***	***30***
MET	/	/	/	16	3	-4.3
LEAK	/	/	/	87	11	-1.5
WEFF	/	/	/		81.2	-1.0
Total demand management	***/***	***/***	***/***	***103***	***96***	***-7***
LFT	98	27	16	87	22	17
TOTAL	***666***	***65***	***60***	***573***	***152***	***39***

Table 14: Discounted costs of activated schemes grouped by type, for both ‘Case 1_maxEXDO’ and ‘Case2_maxEXDO’ runs.

Results show that the level supply from the existing nodes increases compared to Case 1 and Case 2 respectively (compare Table 6 and Table 15). For example, under the dry year critical period scenario, this increases by 659 Ml/d in ‘Case 1_maxEXDO’ and by 737 Ml/d for ‘Case 2_maxEXDO’.

This reduces the extent of use of optional schemes and, consequently, the weighted variable operating costs (compare Table 5 with Table 14). Variable costs mainly decrease for the effluent reuse schemes, i.e. by £M 76 when no demand management schemes are considered (‘Case 1_maxEXDO’) and by £M 71 otherwise (‘Case 2_maxEXDO’).

	Capacity [Ml/d]							
	‘Case 1_maxEXDO’				‘Case 2_maxEXDO’			
	DYAA	DYCP	MDO	NYAA	DYAA	DYCP	MDO	NYAA
MET	/	/	/	/	162	162	162	162
LEAK	/	/	/	/	1796	1796	1796	1796
WEFF	/	/	/	/	190	190	190	190
Total demand management	***/***	***/***	***/***	***/***	***2148***	***2148***	***2148***	***2148***
ASR	212	852	49	27	76	513	44	6
DESAL	28	104	47	7	22	83	43	3
ER	3917	4107	3228	1039	2580	2823	2092	544
GW	1048	2179	988	402	773	1735	753	271
Other	72	134	42	52	72	136	38	32
RES	413	552	442	200	303	372	320	93
SW	1110	1505	1110	69	1502	2184	1269	41
WTW	1401	1861	1466	140	1326	1991	1395	131
TR	1036	1436	1103	251	825	1073	783	162
Total supply-side schemes	***9236***	***12729***	***8475***	***2188***	***7479***	***10910***	***6736***	***1283***
Supply-side+ demand management	***9236***	***12729***	***8475***	***2188***	***9626***	***13057***	***8883***	***3430***
EXDO	129955	147559	125097	129348	129615	147340	124697	128106
Total optional+ existing schemes	***139191***	***160288***	***133572***	***131536***	***139241***	***160397***	***133580***	***131536***

Table 15: Total capacity provided by activated schemes grouped by type, for both ‘Case 1_maxEXDO’ and ‘Case2_maxEXDO’ runs. Existing nodes are referred to as *EXDO*.

Even if the supply from effluent reuse schemes decreases, these schemes still provide the highest volume of supply amongst all optional supply-side schemes (see Table 15). Supply mostly decreases under the normal year annual average scenario (i.e. by 2217 Ml/d in ‘Case 1_maxEXDO’ and by 2612 Ml/d in ‘Case 2_maxEXDO’), compared to the other demand scenarios (see table below). This is because the level of demand under the normal year annual scenario is lower compared to other scenarios. Therefore, if the supply from the existing nodes increases, the deficit and the consequent extent of use of the optional schemes decreases by a higher extent in the normal year annual average scenario than in other scenarios (see Table 16).

	'Case1_maxEXDO'				'Case2_maxEXDO'			
	DYAA	DYCP	MDO	NYAA	DYAA	DYCP	MDO	NYAA
ER reduction	740	680	1493	3326	740	680	1493	3326
% reduction	16%	14%	32%	76%	26%	23%	41%	83%

Table 16: Difference in the extent of use of effluent reuse schemes between Case 1 and 'Case 1_maxEDO', Case 2 and 'Case 2_maxEDO'. The vales are obtained by comparing data in Table 6 and Table 15.

Under the normal year annual average scenario, the supply from scheme 'ER_1080' decreases from 3000 Ml/d in Case 1 to 999 Ml/d in 'Case 1_maxEXDO' and from 2700 Ml/d in Case 2 to 542 Ml/d in 'Case 2_maxEXDO' (Table 9 and Table 17).

	Costs [£M]						
	'Case 1_maxEXDO'				'Case 2_maxEXDO'		
Option Name	WRZ name	Capital	Fixed operating	Weighted variable operating	Capital	Fixed operating	Weighted variable operating
ER_786	WRZ06	15	1	1.5	15	1.2	1.3
ER_1080	WRZ22	147	4	22.6	137	4	13
ER_1074	WRZ22	11	2	0.4	/	/	/
ER_1068	WRZ22	36	4	1.8	/	/	/
ER_1069	WRZ22	6	0.5	0.1	/	/	/
ER_857	WRZ22	4	0.4	0.1	/	/	/
ER_1067	WRZ22	/	/	/	1	0.2	0.04
TOTAL		***219***	***12***	***27***	***153***	***5***	***15***

Table 17: Discounted costs of selected effluent reuse schemes under 'Case 1_maxEXDO' and 'Case 2_maxEXDO' runs.

	Capacity [Ml/d]							
	'Case 1_maxEXDO'				'Case 2_maxEXDO'			
	DYAA	DYCP	MDO	NYAA	DYAA	DYCP	MDO	NYAA
ER_786	285	434	348	6	270	417	350	1
ER_1080	2610	2641	2294	999	2285	2383	1718	542
ER_1074	242	235	76	/	/	/	/	/
ER_1068	663	683	446	34	/	/	/	/
ER_1069	74	69	50	/	/	/	/	/
ER_857	45	45	15	/	25	24	25	-
TOTAL	***3917***	***4107***	***3228***	***1039***	***2580***	***2823***	***2092***	***544***

Table 18: Total extent of use of selected effluent reuse schemes under the four demand scenarios.

2.4.3 Sensitivity runs on LFT links

Case 1 and Case 2 models were run without including water company proposed optional transfers (models 'Case1_noLFT' and 'Case2_noLFT'). Figure 23 shows the evolution over time of the upper and lower bound solutions. The upper bound solution improves rapidly from a 77% relative gap (point A in Figure 23) to a 1.93% one in only 15 minutes. A total running time of 3.3 hours was required, lower than the 45 hours required to run Case 2 with 5.94% relative gap.

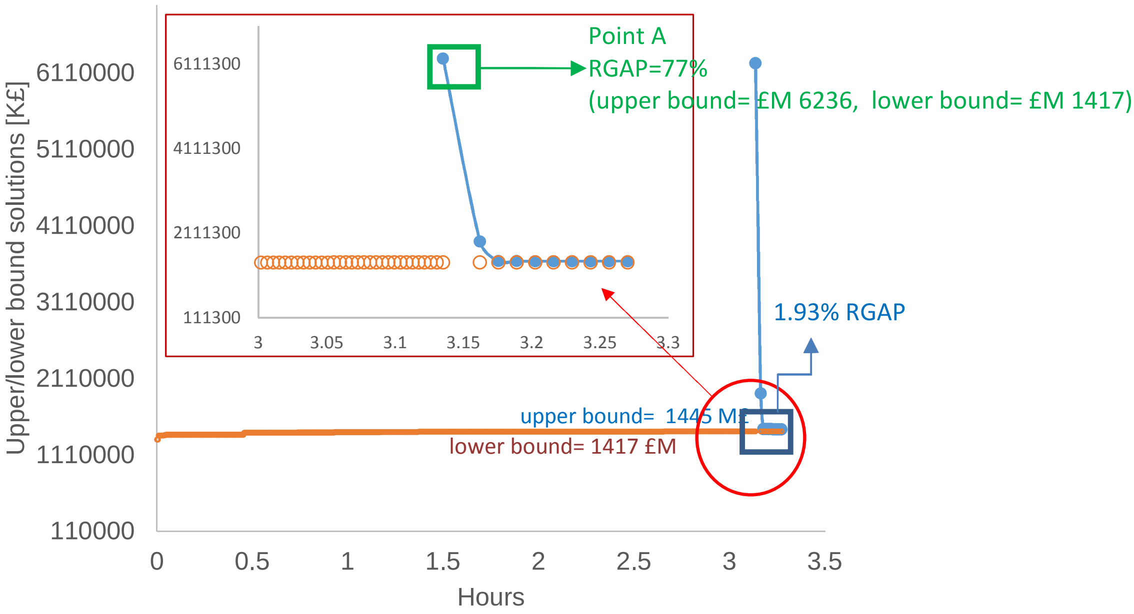

Figure 21: Evolution over time of the upper and lower bound solutions for Case 2_noLFT run. Costs derives from both existing and optional schemes.

	Costs [£M]		
	'Case 2_noLFT'		
	Capital	Fixed operating	Weighted variable operating
ASR	2	0.2	0.2
DESAL	46	6	1
ER	291	9	80
GW	112	8	8.8
Other	44	3	1.9
RES	168	4	3.7
SW	46	10	3.0
WTW	49	3	3.8
TR	34	12	1.4
Total supply-side schemes	***793***	***55***	***104***
MET	28	5	-8
LEAK	217	17	-2
WEFF		83	-1
Total demand management	***245***	***105***	***-11***
LFT	/	/	/
TOTAL	***1038***	***160***	***93***

Table 19: Costs of activated schemes grouped by type, for both 'Case 1_noER' and 'Case2_noER' runs.

Total costs increase from £M 981 in Case 2 (see Figure 20) to £M 1445. This corresponds to a difference of £M 464. Specifically, capital costs increase by £M 427, fixed operating costs by £M 59, and weighted variable costs by £M 4 (Table 5 and Table 19). The increase in capital costs is mostly related to the activation of additional reservoir schemes and to the higher extent of use of effluent reuse schemes.

The volume of supply provided by both demand management and supply-side schemes increases by the 8% in average over the four demand scenarios (compare Table 6 with Table 20).

	'Case 2_noLFT'			
	DYAA	DYCP	MDO	NYAA
MET	280	280	280	280
LEAK	2906	2906	2906	2906
WEFF	191	191	190	190
Total demand management	***3376***	***3376***	***3376***	***3376***
ASR	16	91	19	16
DESAL	55	149	165	5
ER	3468	3800	3639	3227
GW	1047	1980	998	650
Other	271	162	219	138
RES	444	720	412	345
SW	1278	1485	1249	110
WTW	1573	1620	1514	321
TR	653	1505	1387	509
Total supply-side schemes	***8806***	***11510***	***9602***	***5322***
Supply-side + demand management	***12182***	***14886***	***12977***	***8697***
EXDO	127054	145504	120563	122839
Total optional+ existing schemes	***139236***	***160390***	***133540***	***131536***

Table 20: Costs of activated schemes grouped by type, for both 'Case 1_noER' and 'Case2_noER' runs.

The level of network infeasibility also increases compared to Case 2 (Table 7 and Table 21). This shows that some water resource zones cannot meet their deficits without importing water from other water resource zones.

	Deficits [Ml/d] - Case 2_noLFT			
	DYAA	DYCP	MDO	NYAA
WRZ18	/	/	2.7	/
WRZ17	/	2	0.5	/
WRZ13	8	1.3	90	/
WRZ01C	/	/	/	/
WRZ15	/	4.8	/	/
WRZ02	/	1.7	/	/
WRZ01C	5.2	3.4	/	/
TOTAL	***13***	***33***	***93***	***-***

Table 21: deficits in Ml/d under the four demand scenarios and for each water resource zone.

2.4.4 Using starting solutions

Starting solutions can be used to help CPLEX improving convergence. An initial solution might come from a different problem that has been previously solved and that is a feasible solution of the model. A starting solution may include both continuous and discrete variables (such as binary variables or variables appearing in special ordered sets). Assigning an initial solution means specifying the value for any combination of these variables.

Starting solutions were identified from solving sub-problems for both Case 1 and Case 2 models (Figure 22). For example, 'Case1_noER' is a sub-problem for Case 1 where some of the effluent reuse schemes are excluded. 'Case2_noER' and 'Case2_noLFT' are sub-problems of both Case 2 and Case 1 as well.

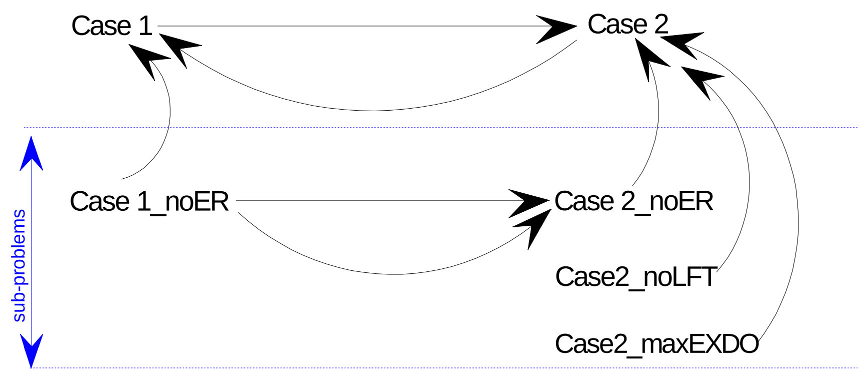

Figure 22: Improving the relative GAP for Case 1 and Case 2 solutions through starting solutions.

Model runs showed that none of the starting solutions improved the evolution of the lower and upper bound solutions.

2.5 Discussion of model results

Including demand management options (Case 2) reduces total net present value costs by the 6% compared to Case 1, which is equivalent to £M 68 (Figure 18). The level of infeasibility also reduces by a maximum of 81% under the dry year critical period scenario (see Table 7). The application of the proposed capacity expansion model to South East England argues in favour of joint supply-side and demand management efforts in order to meet future water demands.

Both Case 1 and 2 models are solved with the CPLEX solver, which uses the branch a bound algorithm introduced in section 2.3. Case 1 model was stopped after about 30 hours with a relative GAP of 2.76%, while Case 2 after 45 hours at a 5.9% relative gap. The inclusion of 511 demand management options in Case 2 corresponds to adding 12,775 additional binary variables (i.e. 511 multiplied by the 25 years of the planning horizon). This increases the model computational burden.

In both Case 1 and Case 2, effluent reuse schemes generate the highest volume of supply (Table 6), as well as the highest capital and weighted variable costs amongst selected schemes (Table 5). Sensitivity analysis was conducted to analyse how the model solution would change under different assumptions on costs and availability of schemes. First, some of the most expensive effluent reuse schemes were deactivated by setting their binary variables equal to zero in Case 1 and Case 2. This increased costs by £M 389 for Case 1 and £M 82 for Case 2 (Table 6 and Table 13) due to an increased level of supply from other scheme types. Specifically, supply increases by 1570 for surface water schemes, 548 Ml/d for leakage reduction measures, and 483 Ml/d imports from external areas. This confirms that surface water schemes, leakage reduction, and import schemes also represent important solutions for the supply-demand balance problem.

A further run was then executed where no costs were associated to the existing schemes. Existing schemes have variable operating costs associated with them, which prevents the model from activating these schemes at the maximum capacity. Results show that the total supply from all optional schemes decreases by 16% on average under the four demand scenarios (see Table 6 and Table 15), while supply from the existing nodes increases. Effluent reuse schemes still provide the highest level of supply amongst all optional supply-side schemes, showing that their implementation is a cost-effective decision.

Finally, all optional transfers were deactivated in Case 2. Results showed that water company proposed regional transfers help reducing the cost on new schemes by 67% (i.e. from £M 1445 to £M 981 in Case 2). If al transfers are deactivated, capital costs increase mostly due to the activation of additional effluent reuse schemes (this increases capital costs by £M 124) and reservoir options (this increases capital costs by £M 157).

2.6 Conclusions

A deterministic capacity expansion model was formulated in this Chapter that finds the least-cost schedule of new supply-side schemes, demand management measures and transfers over a 25 year-long time horizon. The model includes constraints designed to represent the predicted effect of conservation measures on the supply-demand balance. Complex interdependencies between proposed options, which frequently manifest in real systems, are also represented. The model is conservative and assumes planners aim to satisfy peak demands with a prescribed reliability. Multiple simultaneous demand scenarios are considered in order to meet peak demands and accurately estimate variable costs. An infeasibility management procedure is used which reduces demand just enough to allow model feasibility (and warns the analyst), so that the model can still run if certain water supply zones are not able to satisfy intended reliability requirements.

The model is applied to a regional system (South East England) composed of six water utilities serving 17.6 million people. Initially, only new transfers and supply-side schemes were considered (Case 1). Demand management options were added in Case 2. The availability of water conservation schemes in the planning problem reduced the total discounted economic costs by 6% over the 25-year planning horizon. This is due to the implementation of 248 demand management options in place of some of the most capital cost-intensive schemes, such as reservoirs.

Both Case 1 and Case 2 suggest the implementation of effluent reuse schemes with a higher extent than other scheme types. Specifically, effluent reuse schemes provide the 36% and 27% of total supply from optional schemes in Case 1 and Case 2 respectively, under the worst-case scenario (i.e. the dry year annual average scenario). If some of the major effluent reuse schemes are excluded from the analysed network, total costs increase by 27% and 8% in Case 1 and 2 respectively. Furthermore under different assumptions on costs (i.e. by setting costs on the existing schemes equal to zero) and availability of schemes (i.e. company proposed transfers were deactivated) the model recommendation persists, i.e. the optimal extent of use of effluent reuse schemes is higher than other scheme types.

In both Case 1 and Case 2, a first integer solution is found after about three hours. Then, the upper bound solution immediately decreases by about 5% and, after more than 11 hours, by 2-3%. The model convergence does not show any significant improvement afterwards (i.e. the upper bound solution remains constant while the lower bound solution slowly increases by less than 1%). Case 1 model was stopped after 30 hours with a 2.8% ‘gap’ while Case 2 was stopped after 45 hours with a 6% relative ‘gap’. The model’s computational burden decreases when no optional transfer is included in the analysed network (a 1.93% relative gap solution in reached in less than 3.5 hours). The model convergence did not improve by manually setting an initial solution. This implies that setting the initial solution to aid convergence may not be appropriate for EBSD models.

The proposed model is effective at suggesting economically efficient capacity expansion schedules for a large system with 272 interdependency conditions, some quite complex stringing together several proposed schemes. This is demonstrated by the fact that the model selects a restricted subset of schemes out of 827 water company proposed options. Specifically, 97 and 78 supply-side options are selected in Case 1 and Case 2, respectively, out of 316 available supply-side schemes. Furthermore, 248 demand management schemes are implemented in Case 2 out of the 511 available ones. Selected demand management schemes include: 142 water efficiency measures (out of 230), 2 metering options (out of 108) and 104 leakage reduction schemes (out of 173). Finally, 54 and 62 optional transfers are activated in Case 1 and Case 2, respectively, out of 215 available ones.

Chapter 3

FINANCIAL IMPLICATIONS OF REGIONAL WATER TRANSFERS AND UTILITY INTERCONNECTIVITY

3 Introduction

The model introduced in Chapter 2 allows identifying the least-cost schedule of water company proposed schemes (transfers, supply-side and demand management options) for regional water supply-demand networks. The model's ability to identify new inter-company transfers is however limited to only considering those proposed by water companies. This may overlook transfers schemes that could contribute to a lower cost solution. In this Chapter, the model formulation in Chapter 2 is therefore extended to incorporate a generic capital cost estimate for new inter-company transfers not yet proposed in water company plans.

The Chapter is structured as follows: section 3.1 introduces a review of previous studies conducted on the benefits of water transfers; section 3.2 presents the trading water context in England; sections 3.3 and 3.4 introduce the mathematical formulation and its application to the network respectively. Results are described in section 3.5; discussion of results and model limitations are introduced in sections 3.6 and 3.7 respectively, while conclusions are presented in section 3.8.

3.1 Review of previous studies on water transfers

The uneven distribution of water resources, excessive exploitation of some water supplies and increased water demand have often triggered the need to adopt water transfers as an alternative resource under water scarcity (Young, 1986, Trelease, 1965). Transfers help reduce the cost of future capacity expansion by decreasing the need for capital cost-intensive supply-side schemes or costly demand management measures. Transfers can also help reduce abstraction in locations where taking more water out of the environment could damage the wildlife and other habitats (Lund and Israel, 1995).

The literature discussing the advantages of water transfers is vast (Vaux and Howitt, 1984, Wang, 2012, Hadjigeorgalis, 2008) and many studies have been conducted that estimate the benefits of water trading allocations. Vaux and Howitt (1984) considered a regional system of five demands and eight supply regions in California for a three year planning period. The study results highlighted that less than 123 million cubic meters of new supplies would be required in the area if an increased level of sharing of water resources was allowed through additional transfers. Zarghami and Akbariyeh (2012) estimated benefits from additional trading for a city in Iran and showed that both transfers and demand management measures could reduce water shortages in their case-study by up to 45%. Chang et al. (2011) showed that using transfers in conjunction with local water resources for a region in China consistently increases the level of supply reliability. Characklis et al. (2006) used simulation and optimisation modelling to find the least-cost portfolio of transfer options in conjunction with supply-side schemes for urban water planning development. Zaman et al. (2009) incorporated an economic trading model with a hydrologic water allocation model to estimate impacts and potential bottlenecks of temporal water trading and physical water transfers in Australia. Karamouz et al. (2010) used simulation and optimisation modelling techniques to analyse the feasibility of two potential inter-basin transfer projects in Iran. George et al (2011) used an integrated hydro-economic model to evaluate water allocation strategies for river basins or sub-basins.

Unlike most studies that consider the economic returns from water transfers in a market context, this Chapter is centred on trading between large regional utilities. Currently, the regulatory system in England is not designed to incentivise water companies to trade between each other, and so the companies do not typically seek such arrangements. Changing incentives can be costly and entails some level of risk as the English water supply sector is funded through private investors.

3.2 Water trading in the South East of England

The water industry in England faces possible shortages in the South East region, the driest part of the UK (EA, 2005b). Since the early 1990s, water transfers (pipelines and natural river channels) have been suggested to solve supply-demand deficits instead of the traditional supply-fix strategy (Swinnerton and Sherriff, 1993, Cryer, 1995). However historically water companies in England have faced disincentives from developing trades across their borders (Ofwat, 2010d).

Reasons behind low company trading include: A. under the current 2010-2014 price-cap regulation if water companies develop their own water resources, they can earn a return on the associated capital expenditure, whilst importing water from a neighbouring area is classified as an operating cost and no return can be earned on it; B. the presence of regulatory penalties for not meeting expected supply obligations (Water Act 1989) may encourage water companies to count on their own resources rather than on imports from other companies (Ofwat, 2010d); C. trading is not a familiar solution in the South East. A lack of information on supply-costs and future demand levels has often made it difficult to identify new cross-border trades (Severn Trent Water, 2010, Ofwat, 2010d).

Both the Environment Agency and Ofwat are aware of these disincentives (Ofwat, 2010d) and have taken measures to promote an increased level of interconnections in the South East of England. Ofwat (2010c) carried out a study to estimate savings from additional inter-company transfers in England and Wales. Results identified benefits of about £M 1000 compared to the water company resources management plans. The water resources of the South East (WRSE) group, a consortium led by the Environment Agency and composed of Ofwat, Defra and the water companies in the area, carries out EBSD least-cost optimisation modelling to identify new sharing opportunities (bulk supply agreements) in the area. The WRSE model treats the whole network as if it were under the jurisdiction of one water company (regional modelling) and identifies a solution (schedule of new schemes) that is least-cost for the whole region, rather than for the individual companies in the area. Regional modelling carried out in 1990 led to the implementation of four new transfers in the South East region (EA, 2010b). In 2010 the WRSE group identified potential savings of £M 501 by 2035 as a result of more sharing in the area (EA, 2010b).

Both the 2010 Ofwat study (2010c) and the WRSE model have limitations. The Ofwat study (2010c) is based on substantial simplifications: A. it does not support capacity expansion planning, therefore it cannot claim that the identified interconnections are cost-effective; B. benefits from a new interconnection between two water resource zones (WRZs) are roughly estimated as the difference between the highest average incremental social cost (see section 1.5.3) of company proposed supply-side schemes in the two WRZs, minus the cost of the transfer; C. the study only considers pairs of transfers between neighbouring demand zones: greater benefits may be gained if water is allowed to move through ‘chains’ of interconnections passing through intermediate demand zones.

The WRSE model overcomes all the above limitations but its capability of identifying new transfers in the South East area is limited because it only considers the interconnections proposed by water companies. Currently the WRSE network is not fully interconnected. Water resource zones are either only connected to a few of their neighbouring zones (as proposed in water company plans) or not inter-connected at all. This prevents potential transfers from being considered that could contribute to a lower cost solution. The work carried out in this Chapter is supposed to overcome this limitation. In addition to including the water transfers proposed in the water company resource management plans, the WRSE model used in this study was expanded to consider interconnections (referred to collectively by set *INT*) between all neighbouring demand zones. A new model formulation is introduced that allows optimising the *INT* transfers that do not have pre-defined costs. A concave cost curve is used that reflects the economies of scale of building large infrastructures. The curve is approximated by a piece-wise linear function.

Capital costs for *INT* transfers are defined using a non-convex cost curve provided by Ofwat, the economic regulator of water companies in England and Wales. In order to keep the model as a mixed integer linear programming formulation, the cost curve is approximated by a sequence of adjacent linear segments. Fixed operating costs for the *INT* transfers are estimated as a percentage m of the capital expenditure, while unit variable costs are known and given as input into the model. The percentage m and the unit variable costs were provided by Ofwat.

Compared to the model formulation in Chapter 2, all schemes are now identified through their interconnection i,j. Therefore, in place of considering two 'extent of use' variables ($S_{i,t,scen}$ for nodes and $Q_{i,j,t,scen}$ for links), only one set of variables ($Q_{i,j,t,scen}$ for nodes and links) is used. The same is done for the binary variables that determine the activation of schemes ($AL_{i,j,t}$ refers to both nodes and links). The formulation in Chapter 4 and 5 follows this rule as well. This allows reducing the number of decision variables and model constraints and improves the model's computational efficiency. The model formulation is described below. As in Chapter 2, all terms in capital letters represent decision variables or set definitions while those in lower case are the model input data.

3.3 Model formulation

3.3.1 Nomenclature

In addition to the list in Chapter 2 (section 2.1.1), the following terms are introduced:

Indices of Sets

k breakpoints of the piecewise linear function

Sets

INT possible inter-company transfers i,j not proposed by water companies

K set of breakpoints of the piecewise linear function

Parameters

γ_k expansion size at point k of each INT transfer

δ_k undiscounted capital cost at point k of each INT transfer

$dis_{i,j}$ length in kilometres of INT transfers

crf capital recovery factor

Variables

$UNC_{i,j}$ undiscounted capital cost of INT transfer i,j

$Z_{i,j}$ maximum extent of use of INT transfer i,j

$CAL_{i,j,t}$ undiscounted annual capital cash outflow per kilometre length of INT transfer i,j

$CALN_{i,j,t}$ positive variable equal to $CAL_{i,j,t}$ if the INT transfer i,j is selected, otherwise zero

$L_{i,j,k}$ SOS2 variable. It can be greater than zero only for adjacent values of k, i.e. (k_1,k_2), (k_2,k_3), etc.

3.3.2 The objective function

The objective function equation 2.1 in Chapter 2 (referred to as f') is updated to include costs for the INT transfers:

$$minimize\ \ F = f' + \sum_{t=0}^{T} \frac{1}{(1+dr)^t} \left[\begin{array}{l} \displaystyle\sum_{(i,j)\in INT} (1+m) \times CALN_{i,j,t} \times dis_{i,j} \\ \displaystyle + \sum_{(i,j)\in INT} \frac{\sum_{scen} tscen_{scen} \times Q_{i,j,t,scen} \times var_{i,j} \times dis_{i,j}}{\sum_{scen} tscen_{scen}} \end{array} \right] \qquad 3.1$$

where $var_{i,j}$ is the unit variable costs, $Q_{i,j,t,scen}$ [Ml/d] is the extent of annual use variable, $dis_{i,j}$ is the length of transfer i,j of set INT. The variable costs are weighted over the demand scenarios with $tscen_{scen}$ being each scenario's time horizon in number of weeks (see equation 2.15). Capital costs are included as annual time-series of constant cash outflows. $CAL_{i,j,t}$ [k£/km] is a positively defined decision variable representing the annual undiscounted capital cost per kilometre (see the compound interest formula for equal payment series in paragraph 1.3). $CAL_{i,j,t}$ is determined based on transfer i,j's maximum level of utilisation which is optimised by the model. $CAL_{i,j,t}$ is equal to zero until when the transfer is activated at year t^*, and equal to a constant value from year t^* till year T, where T is the final year of the planning horizon.

3.3.3 Piece-wise linear formulation

The non-convex cost function is approximated by a sequence of k segments (piecewise linear function). The slope of each segment decreases at 'breakpoints' (γ_k, ∂_k) where γ_k and ∂_k are the transfer's expansion size and undiscounted capital costs respectively. The piece-wise linear function is expressed by the following set of constraints:

$$UNC_{i,j} = \sum_k \delta_k L_{i,j,k} \qquad \forall (i,j) \in INT, k \in K \tag{3.2}$$

$$Z_{i,j} = \sum_k \gamma_k L_{i,j,k} \qquad \forall (i,j) \in INT, k \in K \tag{3.3}$$

$$\sum_k L_{i,j,k} = 1 \qquad \forall (i,j) \in INT, k \in K \tag{3.4}$$

where $UNC_{i,j}$ and $Z_{i,j}$ are positive decision variables and represent the undiscounted capital costs and the maximum extent of use respectively. $UNC_{i,j}$ and $Z_{i,j}$ are expressed as a linear combination of ∂_k and γ_k (see equations above).

In order to determine the correct value for variable $UNC_{i,j}$, a set of variables $L_{i,j,k}$ has to be used that satisfies the following condition. For each INT link at most two variables in the set $\{L_{i,j,1,\ldots,}\ L_{i,j,k}\}$ can assume positive values, and if there are two positive variables in the set, they must be adjacent (Keha et al., 2006). For example, if the piece-wise linear function is composed of three adjacent segments, then there are four breakpoints: (γ_1, ∂_1), (γ_2, ∂_2), (γ_3, ∂_3), (γ_4, ∂_4). To satisfy the condition stated above, $L_{i,j,k}$ can only assume non-zero values for two consecutive elements of set K, i.e., ($L_{i,j,1}$, $L_{i,j,2}$) or ($L_{i,j,2}$, $L_{i,j,3}$) or ($L_{i,j,3}$, $L_{i,j,4}$).

There are two ways to satisfy this condition. The first one is to introduce a new set of binary variables and constraints (Keha et al., 2004). The second method consists of using a branching technique that adopts a set of variables called 'special order sets of type 2’ or SOS2. MILP models that use SOS2 variables have long been used (Beale and Forrest, 1976) and many studies have been conducted that replace binary variables with special ordered set variables (de Farias et al., 2001, de Farias Jr et al., 2008, Martin et al., 2006, Keha et al., 2004, Keha et al., 2006, Verleye and Aghezzaf, 2013). SOS2 variables allow reducing the number of binary variables, and this helps improve the computational efficiency of the branch and bound algorithm (Keha et al., 2006). The GAMS modelling system embeds a special feature that allows the use of SOS2 variables. In this study, variables $L_{i,j,k}$ are SOS2 variables:

$$L_{i,j,k} \quad SOS2 \qquad \forall (i,j) \in INT, k \in K \tag{3.5}$$

Equation 3.6 defines $Z_{i,j}$ as each transfer’s maximum level of utilisation over the planning horizon and demand scenarios (set *SCEN*).

$$Z_{i,j} \geq Q_{i,j,t,scen} \qquad \forall (i,j) \in INT, t \in T, scen \in SCEN \tag{3.6}$$

Equations 3.3 and 3.6 can be combined into equation 3.7 below:

$$\sum_k \gamma_k L_{i,j,k} \geq Q_{i,j,t,scen} \quad \forall (i,j) \in INT, t \in T, scen \in SCEN \tag{3.7}$$

The annual capital cost $CAL_{i,j,t}$ [k£/year] is obtained by multiplying the undiscounted capital cost $UNC_{i,j}$ [k£] by the capital recovery factor $crf=[ic(i+ic)^{ul}/(i+ic)^{ul}-1]$, where *ic* is the interest rate (see section 1.3). This multiplication returns the value of a series of end-of-year payments of a constant amount, for a number of periods equal to the transfers’ lifetime *ul* (see paragraph 1.3). Variable $CAL_{i,j,t}$ is accounted for starting from the transfers’ first year of activation. Binary variables $AL_{i,j,t}$ change from zero to one when any optional asset *i,j* is selected. The annual capital costs ($UNC_{i,j} \times crf$) are multiplied by variable $AL_{i,j,t}$ (see equation3.8) to force capital costs to be accounted for only if the transfer *i,j* is selected:

$$CAL_{i,j,t} = UNC_{i,j} \times crf \times AL_{i,j,t} \quad \forall (i,j) \in INT, t \in T \tag{3.8}$$

The multiplication of $UNC_{i,j}$ by $AL_{i,j,t}$ in equation 3.8 introduces nonlinearities in the model formulation. In order to keep the model linear, a new positive variable is introduced $CALN_{i,j,t}$ which appears in the objective function equation 3.1, and is constrained by equation 3.9.

$$\left(UNC_{i,j} \times crf\right) - g(1 - AL_{i,j,t}) \leq CALN_{i,j,t} \quad \forall (i,j) \in INT, t \in T \tag{3.9}$$

The meaning of equation 3.9 can be explained as follows. If a transfer i,j of set INT is not selected ($AL_{i,j,t}$=0), equation 3.9 becomes: $CALN_{i,j,t} \geq (UNC_{i,j} \times crf\text{-}g)$, with $CALN_{i,j,t}$ being the transfer's annual capital cost. Term g is a scalar. This is greater than the maximum value for $UNC_{i,j} \times crf$ (g can be estimated from the cost curve). The difference ($UNC_{i,j} \times crf\text{-}g$) is therefore negative. Since costs are minimised (see the objective function equation 3.1) and given that $CALN_{i,j,t}$ is a positive variable, then the model will fix $CALN_{i,j,t}=0$. This means that, if the transfer is not selected ($AL_{i,j,t}$=0), its capital cost is 0 ($CALN_{i,j,t}=0$) in the objective function equation 3.1. If $AL_{i,j,t}$=1 (INT link selected), equation 3.9 becomes: $CALN_{i,j,t} \geq UNC_{i,j} \times crf$ where $UNC_{i,j}$ is defined by equation 3.2 based on the transfers' maximum extent of use (see equations 3.2 and 3.7).

Equations 3.2 and 3.9 can be merged into the equation below:

$$\left(\sum_k \delta_k L_{i,j,k} \times crf \right) - g(1 - AL_{i,j,t}) \leq CAL_{i,j,t} \quad \forall (i,j) \in INT, k \in K, t \in T \qquad 3.10$$

3.3.4 Other model constraints

The objective function equation 3.1 is subject to all constraint equations defined in Chapter 2 plus equations 3.4, 3.5, 3.7, and equation 3.10 for the INT transfers. The infeasibility approach in Chapter 2 is also adopted here (see section 2.1.7.2).

3.4 Application: South East of England water supply

This model is applied to the WRSE network. In contrast to Chapter 2, where the water companies' private data are used, a new version of the WRSE network was built for this study (Figure 23) using the water resources management plans (WRMPs) that companies submitted for the 2010-14 periodic review period (Thames Water, 2010, Veolia Water Central Limited, 2010, Veolia Water South East, 2009, Sutton&East Surrey, 2010, Southern Water, 2009, di Pierro et al., 2009, Portsmouth Water Ltd, 2009, Southeast Water, 2009). Data on the 'private' WRSE network are confidential and could not be used for this study.

The main difficulty of using public data is that the costs for schemes proposed by water companies are aggregated into their net present values. Since the model uses undiscounted costs, these were estimated based on reported net present value costs by assuming a planning horizon of 60 years (UKWIR, 2002b), a 4.5% discount rate and a 4-year construction period. Furthermore, since in the company water resources management plans the reported net present value operating expenditure includes both variable and fixed operating costs, the variable costs were estimated as a percentage of fixed costs based on previous data received from the Environment Agency. Social and environmental economic costs of schemes (Eftec, 2012, EA, 2003) were also estimated from the net present values. The approximated capital and operating cost estimates per scheme are why this study's results should not be used to evaluate specific infrastructure investments. No costs are associated to the existing schemes, since this information was not available from water company management plans. This means that, compared to Chapter 2, for any given water resource zone, the model maximises the extent of use of the existing schemes before activating new options. However, if there are optional schemes with no variable costs that need to be activated to meet the forecast demand, then the model is indifferent between reducing supply from the existing nodes or increasing accordingly the one from the variable cost-free schemes. This is because both strategies result in the same final cost.

The company water resources management plans contained supply and demand data for three demand scenarios: dry year annual average (DYAA), dry year critical period (DYCP) and normal year annual average (NYAA). The NYAA scenario was assumed to occur with an average frequency of 8 out of 9 years while a total occurrence of 1 out of 9 years was considered for the dry year scenarios (DYAA, DYCP) based on average information collected from the WRSE group for work in Chapter 2.

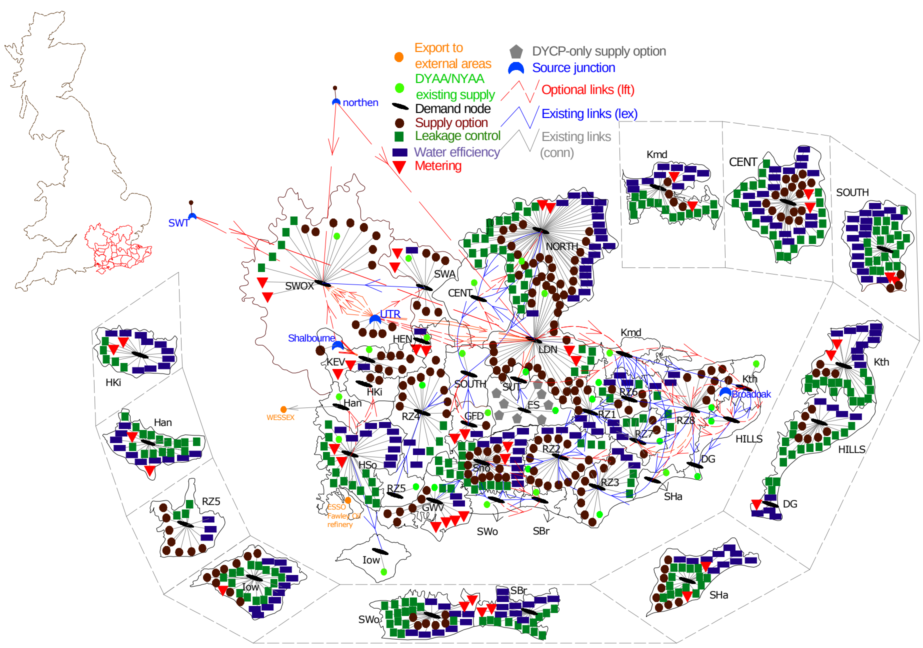

Figure 23: Water supply and demand network of South East England showing 2009 supply and demand management options, as per the water company 2009 water resources management plans.

The capital cost curve for the *INT* links was provided by Ofwat. The curve is an upgraded version of the one published in a previous report (Ofwat, 2010c). The curve gives the total undiscounted capital cost per unit length of transfer as a function of the transfer's expansion size. Its shape is concave reflecting the economies of scale of building large infrastructure. The curve was approximated by a piecewise linear function. The quality of the piecewise linear approximation depends on the number of linear segments. However, increasing the number of segments also increases the number of variables and model constraints. Furthermore, as the cost curve is an approximation in the first place, a precise piecewise linear function may not be necessary. The concave curve used for this application is an approximation because it is based on assumptions on 'fixed costs' (set up costs required to initiate the transfer), rate of cost increase per transfer diameter, and velocity of flow inside the transfer. The cost curve was approximated by three linear segments (see

Figure 28). The segments were selected in order to better approximate the concave cost curve for lower capacities, based on an initial analysis of deficits at the WRZs (deficits were calculated comparing demand with the available supply from the existing nodes).

The curve (or its piece-wise linear approximation) returns capital costs per unit length. The length of the *INT* links was assumed to be the distance between the centres ('centre to centre' distance) of neighbouring water resource zones (WRZ) measured using GIS tools as shown in Figure 24.

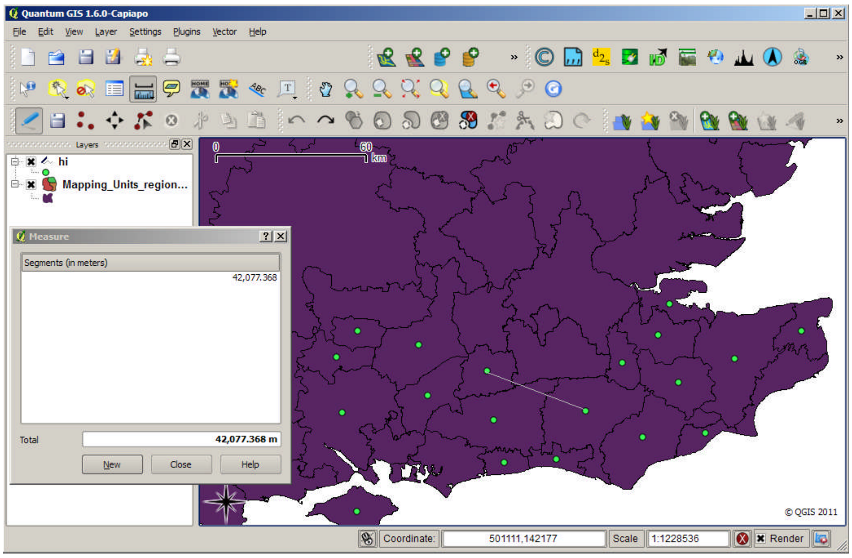

Figure 24: Estimation of the centre-to-centre distance between contiguous water resource zones, in Quantum-GIS.

Since a WRZ is defined as an area where water resources can be shared, ‘there is already some capability of moving water’ within each WRZ (Ofwat, 2010c) and only half of the ‘centre to centre’ distance was considered.

The operating costs in the model were calculated based on information received from Ofwat: fixed operating costs are a fixed percentage of the transfers’ capital expenditure, while unit variable operating costs (due to pumping) are equal to 0.102 p/m^3/km and assume an electrical consumption of 0.0102 kWh/m^3/km and a conservative electricity price of 10 p/kWh.

Nineteen inter-company transfers (set *INT*) were identified which connect WRZs in surplus to neighbouring WRZs in deficit. Surpluses and deficits were calculated by subtracting the WRZs existing supply (nodes EXDO) from the WRZs forecast demands.

In addition to the *INT* transfers, the network also includes: existing transfers (*LEX*), existing nodes (*EXDO*) and schemes proposed in water company resource management plans. Such schemes include: 242 supply-side options, 48 metering schemes, 258 leakage reduction strategies, 186 efficiency measures and 41 company proposed transfers (referred to collectively as *LFT*). As in Chapter 2, demand management schemes have user-defined annual water saving profiles which start from their first year of activation. Some major supply schemes have several discrete capacities and cost values, which are included as separate mutually exclusive nodes. This is the case for Abingdon reservoir, also known as the ‘Upper Thames reservoir’ (*UTR*). The *UTR* is proposed in two different possible sizes (75 Mm^3 or 150 Mm^3). The *UTR* at 150 Mm^3 can be implemented in one or multiple phases.

The proposed model is applied to two different networks which are named: ‘*partial-LFT*’ and ‘*full-INT*’. The ‘*partial-LFT*’ network only includes the companies’ proposed schemes (*LFT* transfers, supply-side options and demand management measures) whereas the ‘*full-INT*’ network considers the extra *INT* interconnections. Both models use the same demand reduction feasibility assurance scheme (see section 2.1.7.2), mass balance constraints, continuity equation and scheme interdependence constraints. The 266 interdependence constraints include mutual exclusivity (55 constraints), pre-requisites (‘and’ 186, ‘or’ 6, ‘with lag time’ 1), mutual dependency (17). A 25 year planning horizon (2010-2034) is considered for both the ‘*partial-LFT*’ and ‘*full-INT*’ network.

3.5 Results

The problem is stated as a mixed integer linear programming formulation and is solved in GAMS using the CPLEX (ILOG, 2007) solver. Table 22 gives the model dimensions for both model runs. A DELL Precision 7500 machine with 24 GB RAM was used for the model runs.

	Model statistics	
	'*partial-LFT*'	'*full-INT*'
Tot number of variables	114,099	114,669
Binary variables	31,373	31,867
SOS2 variables	/	76

Table 22: Model statistics for '*partial-LFT*' and '*full-INT*' runs.

Figure 25 shows the evolution of the upper and lower bound solutions in '*partial-LFT*' (blue line) and '*full-INT*' (red line). Including the 19 additional links (set *INT*) increases the model computational burden, i.e. in '*full-INT*' a 5% relative 'gap' is reached in 12 hours, while in '*partial-LFT*' a 3.3% relative 'gap' is reached in the first 30 minutes and a 0.31% relative 'gap' in less than four hours.

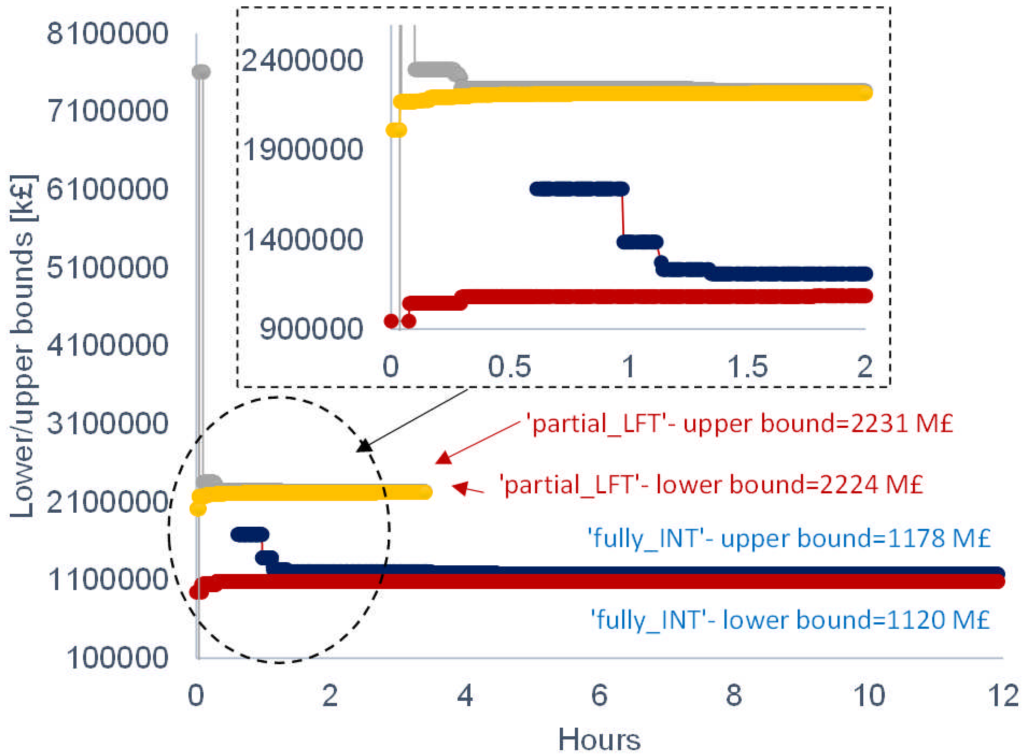

Figure 25: Evolution of the upper and lower bound solutions for the '*partial_LFT*' (see upper blue lines) and '*full_INT*' model.

Total discounted costs decrease from £M 2231 in '*partial-LFT*', to £M 1178 in '*full-INT*'. Table 23 shows the capital expenditure, the fixed and variable operating costs for both model runs. Variable costs are weighted over the three demand scenarios (dry critical period DYCP, dry year annual average DYAA and normal year annual average

NYAA). Supply-side schemes in Table 23 are aggregated by type and include: aquifer storage and recharge (*ASR*); desalination plants (*DESAL*); effluent reuse (*ER*); groundwater utilisation (*GW*); network improvement (*NI*); reservoirs (*RES*); surface water (*SW*); water treatment works (*WTW*), and imports from areas external to the network (*TR*). Demand management options consist of leakage reduction strategies (*LEAK*), water efficiency measures (*WEFF*) and metering schemes (*MET*).

In '*full-INT*', capital costs reduce by 32% (from £M 1279 in '*partial-LFT*' to £M 865), fixed operating costs by 75% (from £M 832 in '*partial-LFT*' to £M 212), while weighted variable costs increase by 14% (from £M 117 in '*partial-LFT*' to £M 101).

	Costs [£M]					
	'*partial-LFT*'			'*full-INT*'		
	Capital	Fixed operating	Weighted variable operating	Capital	Fixed operating	Weighted variable operating
NI	34	5	0.04	5	2	0.03
RES	138	2	0.3	187	1	0.5
TR	347	428	91	331	66	93
WTW	7	2	0.0	10	2	0.1
ASR	133	21	15	/	/	/
ER	40	7	1	14	6	0.1
GW	87	18	0.6	65	19	0.5
DESAL	97	48	8	54	38	6.4
MET	278	14	/	16	-1	
SW	51	3	0.6	50	4	0.1
LEAK	18	288	/	12	73	/
WEFF	49	-3	/	11	-0.5	/
Supply options	***1279***	***834***	***117***	***753***	***210***	***101***
LFT	0.2	2	0.02	1	2	0.04
INT	/	/	/	111	0.28	0.34
INT + LFT	***0.2***	***2***	***0.02***	***111***	***3***	***0.34***
TOTAL	***1280***	***835***	***117***	***865***	***212***	***101***

Table 23: Discounted costs for supply-side options and demand management measures aggregated by option type for '*partial-LFT*' and '*full-INT*' runs. Columns may not add up due to rounding.

Solving the '*partial-LFT*' and '*full-INT*' models also returns the extent of annual use of existing and selected optional schemes (see Table 24). When 19 additional transfers are included ('*full-INT*'), the extra-supply from water resource zones in surplus, or where the costs for new resource development are lower, reduces the need for additional infrastructure or high-cost demand management schemes in the network. For example, the extent of use of 'network improvement' schemes (set *NI*) drops from 368 Ml/d in the '*partial-LFT*' to 49 Ml/d in '*full-INT*' under the dry year critical period scenario (Table 24). Demand management schemes are also used to a lesser extent in the '*full-*

INT' than in '*partial-LFT*'. Alternatively, the extent of use of imports (set *TR*, these are operating expenditure based assets) is higher in '*full-INT*' (under the dry year demand scenarios) than in '*partial-LFT*' (Table 24). Aquifer storage and recharge schemes are not selected in '*full-INT*'. In contrast, in '*partial-LFT*', under the dry year scenarios, these schemes release 666 Ml/d and include: five options in the London water resource zone (see Table 25) and one option in the SWOX zone (Thames Water). The 63% of supply from aquifer storage and recharge schemes (i.e. 418 Ml/d) is due to the activation of a scheme in the London area. This scheme (option 'AS_SLA', see Table 25) generates a total discounted cost of £M 96 (see Table 25), which corresponds to the 64% of total discounted costs for aquifer storage and recharge schemes (Table 23).

	'*partial-LFT*'			'*full-INT*'		
	DYAA	DYCP	NYAA	DYAA	DYCP	NYAA
NI	148	368	124	20	49	3
RES	17	390	/	26	445	2
TR	2894	2939	213	3545	3601	72
WTW	16	60	3	31	53	13
ASR	666	666	433	/	/	/
ER	113	204	113	5	118	5
GW	422	835	31	494	729	62
DESAL	1005	1090	/	872	918	/
MET	1913	1913	1913	681	681	681
SW	141	240	76	100	198	3
LEAK	1657	1657	1657	1219	1219	1219
WEFF	218	218	218	129	129	129
TOTAL	***9210***	***10579***	***4781***	***7122***	***8140***	***2188***

Table 24: Least-cost quantity in Ml/d of activated supply-side and demand management schemes for the '*partial-LFT*' run and the '*full-INT*' run. Costs are discounted to year 2010. Columns may not add up due to rounding.

Supply from optional nodes decreases in '*full-INT'* compared to '*partial-INT*' (see Table 24). This is because the *INT* links allow water to be exported from zones in surplus or where the cost for new infrastructure development is lower.

Figure 26 shows the existing (*LEX*) and optional (*LFT*) transfers selected under both the '*partial-LFT*' and '*full-INT*' model runs. Numbers in Figure 26 correspond to the *INT* transfers' maximum annual level of utilisation [Ml/d]. Transfers proposed by companies (*LFT*) are in red, while the *INT* links are in magenta. Supply and demand management schemes are also activated in both runs but these are not shown to avoid Figure 26 from becoming too cluttered. The top panel of Figure 26 refers to '*partial-LFT*', while the bottom panel shows results from '*full-INT*'. By comparing the two plots in Figure 26, the following differences can be noticed.

In the SWOX water resource zone, an *INT* transfer is activated (panel 'b' of Figure 26) that provides a maximum annual capacity of 58 Ml/d. On the contrary, in '*partial-LFT*' an *LFT* link is selected with a lower maximum annual capacity of 3.3 Ml/d. This means that some of the supply schemes activated in '*partial-LFT*' are no longer selected, but rather replaced by the 34 Ml/d *INT* import. Similarly, surpluses from the HKI and HSO water resource zones (panel 'b', of Figure 26) are exported to zone RZ4 in place of higher cost supply and demand management schemes selected in '*partial-LFT*'.

The *INT* imports with the largest extent of use are located in the London zone (*LDN* in Figure 26), the area with the largest deficit in the region. Total costs in the London zone reduce by 65% (from £M 1606 in the '*partial-LFT*' run to £M 564 in the '*full-INT*' run) due to two *INT* imports from Veolia Water Central. Specifically one *INT* link is activated from the *NORTH* zone with a maximum capacity of 118 Ml/d and the other from the *SOUTH* zone with a maximum capacity of 54 Ml/d (see Figure 26, bottom panel). These two *INT* imports replace supply schemes selected in '*partial-LFT*'. Such as: aquifer storage and recharge, targeted compulsory metering, imports and groundwater schemes (see Table 25). Specifically there are two options that contribute the most to total costs in '*partial-LFT*'. These include import option TR_BTN and a targeted compulsory metering scheme (option M_TCM). These schemes provide, respectively, the 35% (2186 Ml/d) and 25% (1596 Ml/d) of total supply in the London area. Such schemes are no longer selected in '*full-INT*'.

Table 25 shows the capital and operating costs of schemes selected in '*partial_LFT*' and '*fully_INT*', for the London water resource zone. The 73% (£M 1622 in '*Partial_LFT*') and 43% (£M 506 in '*full_INT*') of total costs (compare Table 25 with Table 23) are due to the activation of supply-side and demand management schemes in the London area. A significant amount of capital costs in the London area is due to the activation of the import scheme TR_BT and the metering scheme M_TCM.

		Costs [£M]					
		London 'LDN'					
		'*Partial_LFT*'			'*full_INT*'		
Option name	Type	Capital	Fixed operating	Weighted variable operating	Capital	Fixed operating	Weighted variable operating
TR_ST	TR	30	2	1	30.9	3.4	1.9
TR_BTN	TR	244	42	75	244	42	90
TR_BSS	TR	24	181	8	/	/	/
TR_BSN	TR	18	178	5	/	/	/
AS_ARK	ASR	12	5	3	/	/	/
AS_SLA	ASR	77	7	12	/	/	/
AS_ASR	ASR	8	3	0.1	/	/	/
AS_DV2	ASR	10	1	0.01	/	/	/
AS_DV1	ASR	18	4	0.1	/	/	/
ER_HB	ER	29	2	1.3	/	/	/
GW_ELR	GW	0.1	0.5	0.01	0.1	0.3	0.01
GW_NNR	GW	0.9	0.8	0.01	0.8	0.6	0.02
GW_ECR	GW	1.0	2.5	0.1	0.8	1.6	0.04
GW_SW	GW	3.9	0.8	0.1	3.1	0.6	0.1
DE_ESD	DESAL	14	30	8	13.0	25.6	6.3
M_TCM	MET	246	13	/	/	/	/
AL1	LEAK	1.1	19	/	1.0	15	/
AL2	LEAK	1.1	26	/	0.6	7	/
AL3	LEAK	1.1	38	/	0.5	9	/
AL4	LEAK	1.1	61	/	0.5	7	/
AL5	LEAK	1.1	61	/	/	/	/
EWE_L	WEFF	40	-2	/	/	/	/
TOTAL		***779***	40	-2	***295***	***112***	***99***

Table 25: discounted costs of schemes selected in '*partial_LFT*' and '*fully_INT*' for the London water resource zone.

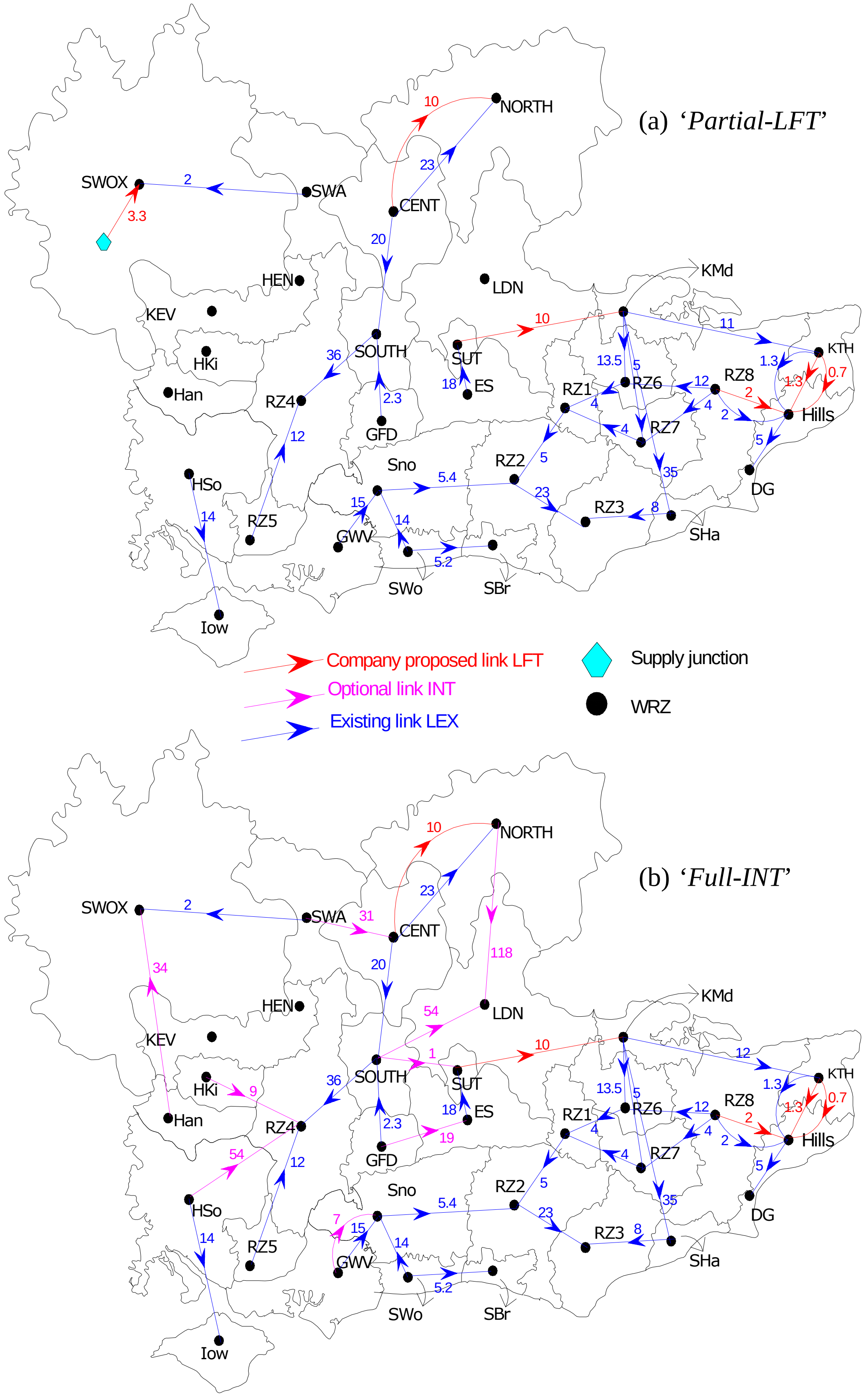

Figure 26: Existing (blue) transfers and selected companies’ proposed *LFT* (in red) and *INT* transfers (in magenta) under the ‘*partial-LFT*’ (top panel) and ‘*full-INT*’ (bottom panel) runs. Numbers state the transfers’ maximum annual extent of use in Ml/d.

The activation of *INT* imports to the London zone increases costs for the *NORTH* and *SOUTH* water resource zones (Veolia Water Central). This is because the surplus of water exported to the London zone is generated in the *NORTH* and *SOUTH* water resource zones through a greater activation or extent of use of optional supply schemes and demand management options (Table 26).

	NORTH WRZ				*SOUTH* WRZ			
	'*partial-LFT*'		'*full-INT*'		'*partially-LFT*'		'*full-INT*'	
	£M	Number	£M	Number	£M	Number	£M	Number
TR	/	/	/	/	/	/	20	2
WTW	/	/	0.05	/	/	/	0.1	1
ER	0.02	1	0.02	1	0.03	1	0.04	1
GW	/	/	/	/	1.2	5	13	11
LEAK	0.5	18	3	21	1.2	20	8.4	23
WEFF	0.26	2	0.4	6	0.1	1	2	7
Total	***0.8***	***21***	***4***	***28***	***2.5***	***27***	***44***	***45***

Table 26: Discounted costs and number of options selected in the *SOUTH* and *NORTH* water resource zone for both the '*partial-LFT*' and '*full-INT*' model runs. Options are aggregated by type.

3.5.1 Analysis of 'partial-LFT' model

Both '*Partial-LFT*' and Case 2 (Chapter 2) models are applied to study investment decisions in the South East of England. However, the two models use different input data; the '*Partial-LFT*' network was built based on water company resources management plans published online in 2009, while the one in Case 2 uses water company private data from the 2013 resources management plans. Furthermore, the '*Partial-LFT*' input data is approximated since it is extrapolated from net present value costs information that is available online (see section 3.4). The aforementioned reasons explain why '*Partial-LFT*' and Case 2 networks differ in both their topology and input data, even if both of them refer to the South East of England.

Section 3.5.1.1 provides a more detailed analysis of '*Partial-LFT*' model results and justifies the differences between '*Partial-LFT*' and Case 2 model. Sensitivity analysis is then applied in section 3.5.1.2 to validate the '*Partial-LFT*' model solution.

3.5.1.1 Analysis of the main differences between Case 2 and 'partial_LFT'

This section analyses the main differences between '*Partial-LFT*' and Case 2 model solutions. By comparing Table 5 (Chapter 2) with Table 23 in section 3.5, the following major differences are observed. The capital expenditure on reservoir schemes increases from £M 11 in Case 2 to £M 138 in '*partial_LFT*' and the one on imports TR increases from £M 15 in Case 2 to £M 347 in '*partial_LFT*'. Capital costs for metering schemes increase by £M 188. On the contrary, the capital expenditure on leakage and effluent reuse schemes decreases by £M124 and £M 127 respectively, compared to '*partial_LFT*'. Sensitivity analysis also is carried out in section 3.5.1.2 to provide further insights.

The 82% of capital costs in '*partial_LFT*' is due to the activation of a reservoir scheme (option 'RES_064') in water resource zone RZ2. This scheme provides a total maximum capacity of 295 Ml/d over the dry year critical period scenario. Case 2 network has four reservoir options available in the equivalent zone 'WRZ13', however none of these is selected. In contract, smaller options are implemented which include: seventeen water efficiency schemes, 6 leakage reduction measures, 3 groundwater options and 1 water treatment works scheme (Table 27). Deficits in water resource zone RZ2 are lower than in 'WRZ13', which explains why the total level of supply (Table 27) is higher in '*partial_LFT*' than Case 2. Table 27 below shows costs (£M) and capacities (Ml/d) of activated scheme types in 'WRZ13' (Case 2) and 'RZ2' ('*partial_LFT*').

	Case 2			'*Partial_LFT*'		
	WRZ13			RZ2		
	Capital [£M]	Fixed + Weighted variable operating [£M]	Capacity [Ml/d]	Capital [£M]	Fixed + Weighted variable operating [£M]	Capacity [Ml/d]
NI	/	/	/	2	0.4	7
RES	/	/	/	114	-2.2	304
TR	/	/	/	40	24	110
WTW	28	3	50	5	1.5	34
ER	/	/	/	36	0.7	2
GW	167	11	141	3	0.8	36
LEAK	5	0.4	10	3	2	21
WEFF	/	158	13	2	/	3
TOTAL	***200***	***171***	***214***	***205***	***27***	***518***

Table 27: Comparison of schemes selected under Case 2 and '*partial_LFT*' model.

The total capital expenditure on company proposed links (*LFT*) decreases from £M 87 in Case 2, to £M 0.2 in '*partial_LFT*'. Case 2 includes 215 company proposed transfers, while '*partial_LFT*' only includes 41. Out of the 41 links, only 21 interconnect water resource zones and represent company bulk transfer agreements, while the remaining 20 links join shared supply-side schemes with multiple water resource zones. In '*partial_LFT*', only five transfers are selected (in magenta in Figure 26), four of which represent extensions in time of already existing bulk-supply agreements. Such links have therefore no capital expenditure but only fixed and variable operating costs. Only one link (from the SUT to the KMD zone, Figure 26) has a capital cost (£M 0.204), since it represents a 'newly activated' link, and not an extension of an existing one.

The capital expenditure on imports TR from external areas increases from £M 15 in Case 2 to £M 347 in '*partial_LFT*', while capital costs on effluent reuse schemes decrease from £M 305 in Case 2 to £M 40 in '*partial_LFT*'. The 76% of the capital expenditure on effluent reuse schemes in Case 2 is due to the activation of option 'ER_1080' in the London water resource zone (zone 'WRZ22', see section 2.4). Such scheme has a maximum annual capacity of 150 Ml/d. The equivalent water resource zone in '*partial_LFT*' is referred to as 'LDN'. No effluent reuse scheme is selected in the London area in '*partial_LFT*' out of two mutually exclusive available schemes ('ER_100' and 'ER_25', Table 28). In contrast, two imports ('TR_BTS' and 'TR_BTN') are selected. These have a maximum annual capacity of 220 Ml/d. Option 'TR_ST' (Table 28) is the 'Columbus' transfer (import from third party resources west of the Severn estuary), while 'TR_BTN' and 'TR _BTS' are respectively bulk sea imports by tankers from Norway and Scotland. Finally, in Table 28 , 'TR_BSS' and

'*partial_LFT*'					Case 2				
Option name	Capital [£M]	Fixed operating [£M]	Weighted variable operating [£M/m^3]	Cap. [Ml/d]	Option name	Capital [£M]	Fixed operating [£M]	Weighted variable operating [£M/m^3]	Cap. [Ml/d]
ER_100	436	3.8	0.06	100	ER_1077	123	0.43	0.03	150
ER_25	60	2.0	0.01	25	ER_851	117	0.69	0.02	150
ER_HB	31	0.2	0.005	4.9	ER_1080	116	0.33	0.01	150
TR_ST	81	3.2	0.1	39	ER_1071	115	0.82	0.02	150
TR_BTS	332	0.6	4.8	220	ER_1076	87	0.34	0.03	100
TR_BTN	362	5.4	0.2	220	ER_849	83	0.51	0.02	100
TR_BSS	27	14.3	0.1	16	ER_1079	81	0.27	0.01	100
TR_BSN	20	14.1	0.1	11	ER_1070	81	0.77	0.02	100
/	/	/	/	/	TR_1108	138	0.65	0.03	98
/	/	/	/	/	TR_1107	107	1.09	0.03	98
/	/	/	/	/	TR_865	46	1.4	0.03	71
TOTAL	***1349***	***44***	***5.4***	***636***	***TOTAL***	***1094***	***7.3***	***0.25***	***1267***

Table 28: Undiscounted costs [£M] and maximum annual capacity [Ml/d] of available imports TR and effluent reuse schemes (ER) for the London water resource zone LDN and model '*partial_LFT*'.

‘TR_BSN’ are respectively, bulk sea import via bags from Norway and Scotland.

Import ‘TR_BTN’, selected in ‘*Partial_LFT*’, is used with a maximum annual capacity of 214 Ml/d. No other scheme can provide this level of supply alone. For example, if the 100 Ml/d effluent reuse scheme (‘ER_100’) was selected, the undiscounted capital cost would have been higher (£M 436 for ‘ER_100’ and £M 362 for ‘TR_BTN’) and the activation of another scheme would have been needed to reach a total supply of 214 Ml/d. This is the reason why imports schemes are preferred to effluent reuse schemes in ‘*partial_LFT*’. In Case 2, effluent reuse scheme ‘ER_1080’ is activated in year 2022 with a capacity of 150 Ml/d over the planning period. Available imports TR cannot provide the same level of supply (Table 28).

Option name	Water resource zone	Model	Water company	Cost [£M] Capital	Cost [£M] Fixed operating	Cost [£M] Weighted variable operating	Capacity [Ml/d]
SMART	DG	‘*partial_LFT*’	VWSE	0.1	0.1	/	0.5
M_TCM	LDN	‘*partial_LFT*’	THM	246	13	/	1596
S_TCM	SWOX	‘*partial_LFT*’	THM	18	1.5	/	40
COM_H	HAN	‘*partial_LFT*’	SWS	0.9	0.0	/	18
COM_K	KMD	‘*partial_LFT*’	SWS	12	-1.3	/	371
COM_S	SBR	‘*partial_LFT*’	SWS	13	-0.9	/	274
Total Metering - ‘*partial_LFT*’				290	12.4	/	2299
MET1223	WRZ32	Case 2	VWC	7	1.3	-1.9	72
MET1212	WRZ35	Case 2	VWC	12	2.1	-3.2	118
Total Metering - Case 2				19	3.4	-5	190

Table 29: Optimal costs and capacity of selected metering schemes in Case 2 and ‘*partial_LFT*’.

Another major difference between Case 2 and ‘*partial_LFT*’ is represented by selected metering and leakage reduction schemes. Capital costs on metering schemes increase from £M 19 in Case 2 to £M 278 in ‘*partial_LFT*’, while those on leakage reduction schemes decrease from £M 142 Case 2 to £M 18. Table 29 shows the cost and optimal capacity of selected metering schemes in Case 2 and ‘*partial_LFT*’. In Table 29, ‘VWSE’ stands from Veolia Water South East, ‘THM’ for Thames Water, SWS for Sothern Water and ‘VWC’ for Veolia Water central. Furthermore, SMART is a smart metering scheme (water meters connected to a wireless network), while ‘TCM’ and ‘COM’ stand for ‘targeted compulsory metering’ and ‘change of occupancy metering’. ‘MET1223’ and ‘MET1212’ are also ‘change of occupancy metering’ schemes.

The 85% of capital costs on metering schemes in '*partial_LFT*' is due to the activation of option 'M_TCM' in the London area (Table 29). The total optimal supply from this scheme is equal to 1596 Ml/d (annual capacity of 88 Ml/d). Only two other schemes in the London area can provide an annual capacity of 88 Ml/d: effluent reuse option 'ER_100' (maximum capacity of 100 Ml/d), and reservoir scheme 'RES_RM' (maximum capacity of 190 Ml/d). These schemes, however, have higher capital and operating costs than 'M_TCM', and therefore are not selected in '*partial_LFT*'.

No metering scheme is selected in Case 2 within the London zone. This is because metering schemes have higher fixed operating costs per unit capacity compared to other scheme types (see Table 30). Furthermore, metering schemes (maximum annual capacity of 56 Ml/d) are mutually exclusive to leakage options, which have lower capital and operating costs (see Table 30) a total higher maximum capacity of 277 Ml/d. For this reason, leakage schemes are preferred to metering options. The 91% of discounted capital costs on leakage schemes (see Table 5) is due to the activation of one option in the London area (maximum annual capacity of 72 Ml/d, £M 129 capital costs and £M 6 savings).

	Case 2		
	London water resource zone 'WRZ22'		
Option name	Average capital cost/capacity [£M/(Ml/d)]	Average fixed operating cost/capacity [£M/(Ml/d)]	Unit variable operating cost [pence/m^3]
ASR	501	17	34
DESAL	1362	11	25
ER	836	12	21
GW	197	11	18
LEAK	151	-7	/
MET	301	31	/
RES	880	-11	5
SW	694	14	80

Table 30: Average costs per capacity for available optional scheme types available in Case 2.

3.5.1.2 Sensitivity analysis

Sensitivity analysis is conducted to analyse how the '*partial_LFT*' model solution would change based on different assumptions on availability of schemes. First, reservoir option 'RES_064' in water resource zone RZ2 is deactivated (this generates 82% of total capital costs in '*partial_LFT*'). This model run is referred to as '*partial_noRES_064*'.

	Costs [£M]					
	‘*partial_noRES_064*’			‘*partial_noLFT*’		
	Capital	Fixed operating	Weighted Variable operating	Capital	Fixed operating	Weighted Variable operating
NI	36.6	33	5	33	5	0.04
RES	146	136	0.33	136	0.33	0.28
TR	355.0	348	432	348	432	91
WTW	9.4	7	2	7	2	0.02
ASR	134.6	138	21	138	21	15
ER	123.0	45	10	45	10	1.50
GW	106.9	76	16	76	16	0.52
DESAL	54.7	98	48	98	48	8
MET	260.1	302	14	302	14	-
SW	50.8	49	3	49	3	0.62
LEAK	18.0	21	289	21	289	-
WEFF	55.3	51	-3	51	-3	-
LFT	0.2	33	5	/	/	/
TOTAL	***1350***	***1305***	***837***	***1305***	***837***	***117***

Table 31: List of all optional schemes when reservoir scheme ‘RES_094’ is not selected. Numbers may not add up due to rounding.

Total costs increase by £M 142 compared to ‘*partial_LFT’*, capital costs by £M 8 (from £M 138 ‘*partial_LFT*’ to £M 146). This is because another reservoir scheme (‘RES_079’) is activated in zone *RZ3* (discounted capital cost of £M 115). Supply from ‘RES_079’ is exported to zone RZ2 through an existing link.

Optional links *LFT* are then excluded from selection (model ‘*partial_noLFT*’, see Table 31). This improves the model convergence, i.e. a 1.5% GAP solution if found in less than 20 minutes with a total cost of £M 2259. Capital costs increase by £M 26 compared to ‘*partial_LFT*’ (Table 23 and Table 31), while total operating costs increase by £M 3. The increase in capital expenditure is due to the activation of an additional metering scheme in the ‘KMD’ water resource zone (this increases discounted capital costs by £M 15), and to the earlier activation a metering scheme in the SWOX area (this increases discounted capital costs by £M 8).

Finally, two further runs were then executed where imports ‘TR_BTS’ and ‘TR_BTN’, (model ‘*partial_noTR_LDN’*) and metering schemes ‘TCM_L’ and ‘COM_L’ (model ‘*partial_noMET’*) were deactivated. Results are shown in Table 32. Total costs in ‘*partial_noTR_LDN’* increase by £M 300, compared to ‘*partial_LFT*’. This is due to the activation of an additional reservoir scheme in the London zone (£M 729 discounted capital costs, maximum capacity of 2391 Ml/d).

	Costs [£M]					
	'partial_noTR'			*'partial_noMET'*		
	Capital	Fixed operating	Weighted Variable operating	Capital	Fixed operating	Weighted Variable operating
NI	32	4	0.04	34	5	0.049
RES	914	-10	0.5	187	0.3	0.435
TR	140	232	11	536	452	147
WTW	7	2	0	7	2	0.05
ASR	136	22	15	132	21	16
ER	85	26	14	81	23	12
GW	84	18	1	107	18	1.3
DESAL	55	43	6	73	51	12
MET	277	19	/	28	-3	/
SW	51	3	1	53	3	0.6
LEAK	16	281	/	16	283	/
WEFF	48	-3	/	47	-3	/
LFT	0.2	2	0.02	0.2	2	0.025
TOTAL	***1846***	***639***	***47***	***1300***	***855***	***189***

Table 32: Discounted costs for schemes selected in '*partial_noTR_LDN*' and '*partial_noMET_LDN*'. Schemes are grouped by type. Numbers may not add up due to rounding.

Costs in '*partial_noMET*' increase from £M 2231 in '*partial_LFT*' to £M 2344. Specifically, capital costs in the London area decrease by £M 9, while fixed and weighted variable operating costs increase by £M 44 and £M 71, respectively. The increase in the operating costs is due to the activation of an additional import scheme (option 'TR_BTS') and to the earlier activation of import options. Table 33 shows the capital and operating costs of imports selected in '*partial_LFT*' and '*partial_noMET*'.

	Costs [£M]					
	'partial_LFT'			*'partial_noMET_LDN'*		
	Capital	Fixed operating	Weighted Variable operating	Capital	Fixed operating	Weighted Variable operating
TR_ST	/	/	/	62	32	18
TR_BTS	/	/	/	121	0.45	22
TR_BTN	244	42	76	255	46	91
TR_BSS	23	181	8	23	181	9
TR_BSN	18	177	/	17	17	6
TOTAL	***285***	***400***	***88***	***478***	***276***	***146***

Table 33: Costs for activated imports *TR* in model '*partial_LFT*' and '*partial_noMET*' in the London area. Numbers may not add up due to rounding.

3.6 Discussion of results

This Chapter presents an expanded version of the model formulation introduced in Chapter 2. The model (referred to as '*full-INT*') can be used as a tool to identify new economic water supply interconnections which have not yet been proposed by water companies in their water resources management plans. The model results were compared to those obtained by only considering companies' proposed transfers ('*partial-LFT*'). Both models use approximate cost estimates extrapolated from aggregated net present value figures in the company water resources management plans. Costs for the additional interconnections are defined through a concave cost function approximated by a piecewise linear function.

Results show that by only interconnecting water resource zones in surplus with those in deficit (additional 19 links), total discounted costs are reduced by 47%. The selected additional transfers reduce costs by £M 1053 (from £M 2231 in the '*partial-LFT*' run to £M 1178 in the '*full-INT*' run) by drastically reducing the need for additional capital cost intensive supply-side schemes and high cost demand management options in areas in deficit. Specifically, the capital expenditure decreases by 32%, while the fixed and weighted variable operating costs decrease by 75% and 14% respectively.

In the London water resource zone, two *INT* imports reduce the net present value costs by 68% (from £M 1606 in the '*partial-LFT*' run to £M 506 in the '*full-INT*' run) due to the decreased extent of used of 'aquifer storage and recharge' schemes and due to a compulsory metering scheme that is no longer activated. The 73% and 43% of total costs in '*partial-LFT*' and '*full-INT*' respectively, derive from the activation of schemes in the London zone, the one with the highest deficit in the whole network. Specifically, import (option TR_BTN) and compulsory metering (option M_TCM) schemes, generate together the 62% of total discounted capital costs in '*partial-LFT*'. Scheme M_TCM is no longer selected in '*full-INT*' (imports from neighbouring zones are selected in place of M_TCM).

In '*partial-LFT*', the 83% of discounted capital costs on reservoir schemes is due to the activation of a reservoir in zone RZ2. If this scheme is deactivated, the model selects another reservoir scheme in the adjacent zone RZ3 (the supply from this scheme is then exported to zone RZ2, through an existing link). If selected import and metering schemes in the London area are in turn deactivated, total costs increase by £M 300 and £M 113 respectively (due to the selection of additional reservoir and import schemes in the London zone). This demonstrated that imports and metering options represent important solutions doe the analysed supply demand balance problem.

Finally, if the company proposed links are excluded, discounted costs increase by £M 26 due to the activation of additional metering schemes. The *LFT* links only generates

£M 2.2 in ‘*partial-LFT*’ and ‘*full-INT*’. This is because, out of the five selected transfers, four of them represents extension in times of already existing bulk transfer agreements, and therefore have no capital costs associated.

3.7 Discussion of model limitations

Limitations of the ‘*full-INT*’ model are listed below:

1. ‘*Full-INT*’ is a regional model. This means that it finds a solution to the supply-demand balance problem that is a least-cost solution for the whole region rather than for the individual water companies in the area. A regional least-cost solution may not necessarily be the least cost solution for each individual company for two main reasons:

a. suppose that the regional model recommends a transfer from company ‘A’, which is in surplus, to another company ‘B’ in deficit. Company ‘B’ may not accept this solution if it is more expensive than its own solution which does not involve transfers.
b. suppose the regional model activates a number of options in company ‘A’ to fix a deficit in company ‘B’. Company ‘A’ may not accept this solution if it generates costs greater than those needed to solve its own deficit. In situations like this, company ‘A’ may expect appropriate cost sharing or bulk supply incomes from company ‘B’. This is the case of the London water resource zone (Thames Water), which imports surplus water from two neighbouring zones (NORTH and SOUTH) belonging to company Veolia Water Central. The surplus water is generated by activating additional supply-side schemes in Veolia Water Central. This increases costs from £M 0.8 to £M 4 in the SOUTH zone and from £M 2.4 to £M 44 in the NORTH zone, while costs in the London area reduce by £M 311 (metering schemes previously selected for £M 246 are no longer activated).

2. One of the major difficulties of the ‘*Full-INT*’ model is its computational burden. If water companies’ proposed links only are considered, the model converges to a 0.3% relative ‘gap’ in less than three hours. When 19 additional transfers are added (to interconnect water resource zones in surplus with neighbouring zones in deficit), the model reaches a 5% relative ‘gap’ in twelve hours. Finally, when the number of links is increased to 92 (all neighbouring water resource zones belonging to different water companies are interconnected) the model converges to a 28% relative ‘gap’ in 14 days (see Figure 27). Having a relative ‘gap’ greater than zero means that the difference

between the best 'relaxed' and the best integer (BI) solution identified by the model is greater than a fraction of the incumbent objective's value BI. If the branch and bound search tree was fully explored, a smaller best integer solution could have been identified from: a. the improvement in the 'relaxed' solution at subsequent nodes of the branch and bound tree; b. the improvement of the 'best integer' solution (identification of new incumbents).

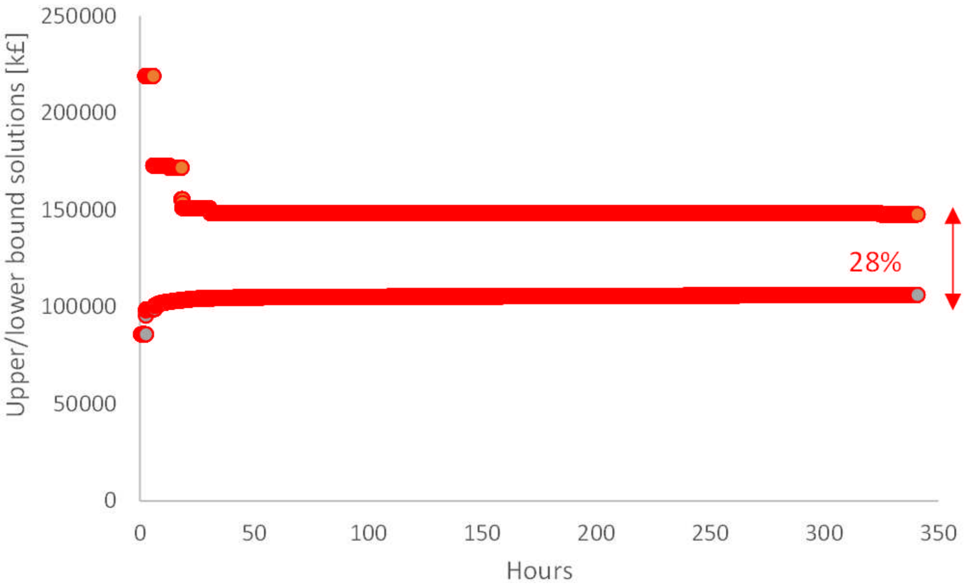

Figure 27: Evolution of the upper and lower bound solution when the number of additional links is increased from 19 in '*full_INT*' to 92.

The model convergence did not improve by manually setting an initial solution. Specifically starting solutions were obtained from running g: a. '*partial_LFT*'; b. '*full_INT* 'with 19 links; c. *full_INT*' with 92 links where the piecewise linear cost function was replaced by a line that joins its extreme breakpoints (see problem P1 in Figure 28).

3.7.1 Deriving sub-optimal results

This section provides a summary of the work conducted to derive a sub-optimal solution for an expanded version of the network shown in Figure 23. This network has 137 *INT* transfers that connect all neighbouring water resource zones, even where these interconnections are already proposed in company resources management plans (in this case, the *INT* links represents an expansion of the proposed transfers). A fully interconnected network allows the optimisation model to select among a greater amount of chains of interconnections passing through intermediate water resource zones. The expanded network also has different input data where scheme costs (extrapolated from the net present value figures in water company resources management plans) were later improved returning the network in Figure 23.

For this network, the branch and bound algorithm failed to identify an integer solution. Therefore, the following strategy was adopted to obtain a sub-optimal solution. The problem (referred to as PP) was decomposed into sub-problems that contain the feasible solution of the original problem (see Figure 28). These sub-problems, referred to as P3, P2, and P1, simplify the model formulation with the degree of simplification increasing from P1 to P3. The simplification allows the reduction in the number of binary variables and model constraints and therefore the model's computational burden.

In sub-problem P3 the cost function is a represented by a line passing from the origin of the axis, as in Figure 28. In sub-problems P1 and P2 the piecewise linear function is replaced by one unique line passing through its extreme points. For sub-problem P1 costs were estimated based on the *INT* transfers' annual maximum level of use, while in P2 costs were calculated based on the transfers' maximum extent of use over the whole planning horizon.

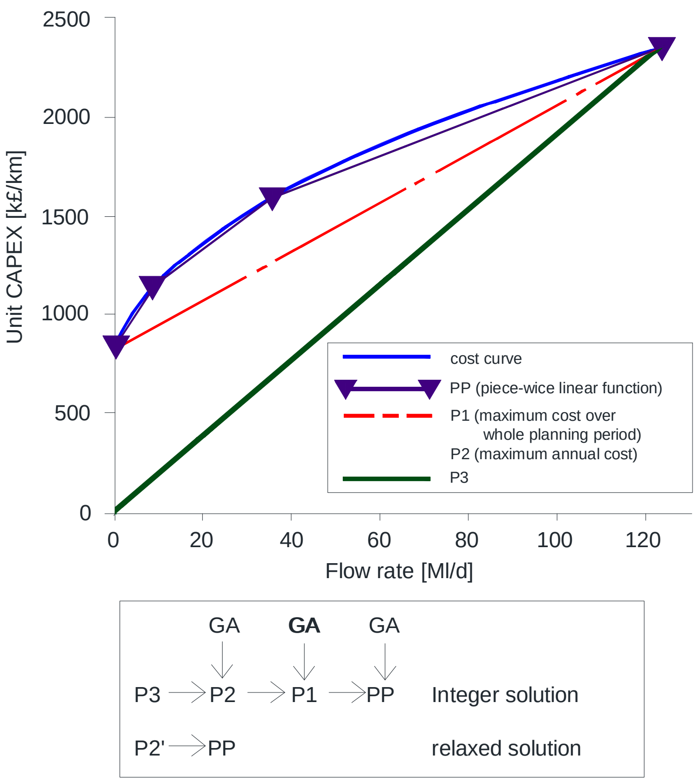

Figure 28: Definition of the sub-problems to solve problem PP.

The solution obtained for sub-problem P3 was then used as the starting solution for sub-problem P2. This was done in order to aid the CPLEX solver in finding an initial solution to the problem (ILOG, 2007). The solution from sub-problem P2 was given as input into P1 as shown in Figure 28. For these runs, the CPLEX platform was used (not within GAMS). Within CPLEX, a predefined feature can be used that allows genetic algorithms (GA) to be called at each node of the branch and bound algorithm as a solution-improvement method. Based on the results presented in (Armbruster et al., 2006), using a GA together with the branch and bound algorithm can improve the computational efficiency of the model.

Each sub-problem was ran until the branch and bound algorithm was not able to improve its convergence to a lower GAP (see Figure 29). At this point the model was stopped and the solution obtained was taken as the best possible integer solution for the analysed sub-problem. Since sub-problems P1 and P2 could not be solved to global optimality, the GA was called within the branch and bound algorithm to reduce run times. A total time of about four days was required to solve sub-problems P3, P2, P1. Seventeen hours were required to find the integer solution for the original problem PP.

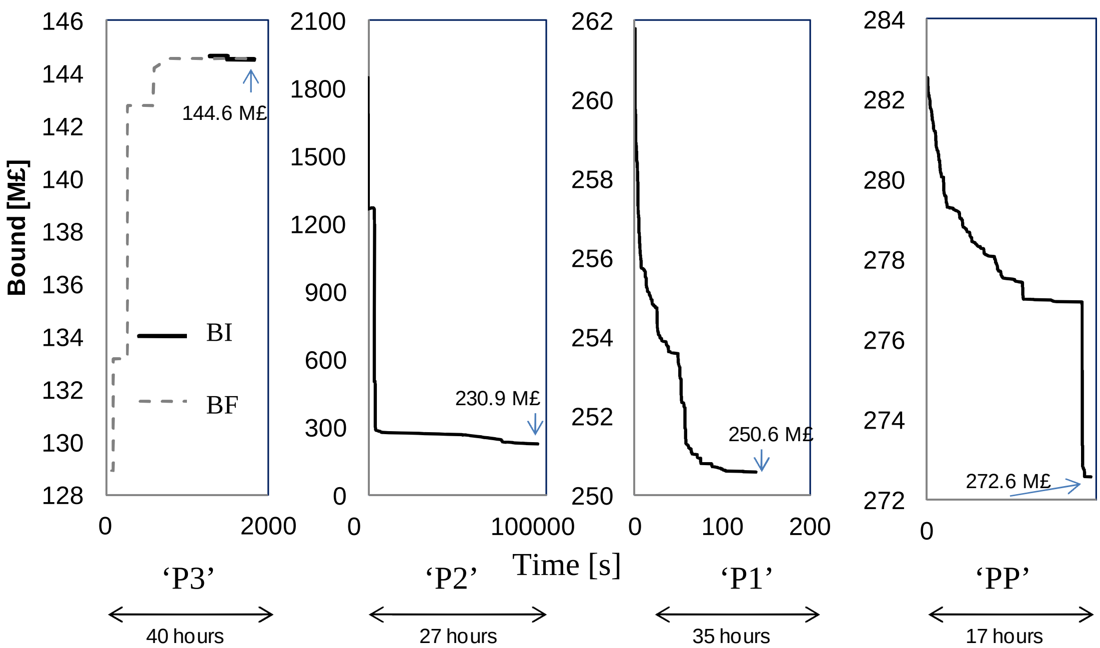

Figure 29: Improvement over time of the integer solution identified by the branch and bound algorithm, for sub-problems P3, P2, P1 and the original problem PP.

The solution obtained from problem PP was considered to be the best possible integer solution with a total discounted cost of £M 272.6 (see Figure 29). To ascertain the quality of this solution, another sub-problem was solved, P2'. In P2' the cost function is represented by the piece-wise linear function in Figure 28, however costs for the *INT* transfers change annually based on the transfers' annual extent of use. Solution from sub-problem P2' (total cost of £M 253.4) results in a lower bound for problem PP. This means that costs for problem PP can decrease up until they are equal to the costs for sub-problem P2', i.e., by 7% (£M 272.6 minus £M 253.4 divided by one hundred). A 7% range of error was considered acceptable for the reasons explained in section 3.5.

3.8 Conclusion

This Chapter presents an extension to the mixed integer model formulation introduced in Chapter 2. This extension allows the incorporation of a generic capital cost estimate for new inter-company transfers not yet proposed in water company plans. Costs for these transfers are defined by a concave cost curve to represent the economies of scale of building large infrastructure. The non-convex cost curve was approximated by a piecewise linear function. The piecewise linear approximation was implemented by using a branching technique that works on sets of variables known as ‘special ordered sets of type two’ (or SOS2). In a SOS2 set only two adjacent variables can assume non-zero values. This is done to avoid the introduction of additional binary variables and constraints that could decrease the computational efficiency of the branch and bound algorithm.

The network was first expanded with 19 additional transfers to interconnect neighbouring water resource zones in surplus with neighbouring zones in deficit. Model results show that a total discounted savings of about £1 billion can be achieved when more transfers are allowed in South East England. This is because the inter-company transfers allow re-allocating the surplus water generated by the existing schemes to zones in deficit. Surplus water is also generated by activating schemes in zones where the cost of developing new infrastructure or demand management measures is lower than in those that would incur a deficit. The model is then expanded to include 92 links to interconnect all neighbouring water resource zones belonging to different water companies. This increased the computational burden, i.e. a 28% relative gap was reached over 14 days meaning that the identified model solution can deviate up to 28% in cost from the least-cost plan. If the number of links is increased to 137 (fully interconnected network) the model cannot even identify an integer solution. In order to identify a sub-optimal solution, the problem was split into sub-problems (containing the feasible solution of the original problem). Genetic algorithms were integrated within the branch and cut algorithm to improve the algorithm’s computational efficiency. This experiment demonstrates that mathematical programming may not be suitable for large-scale networks. This raises the question of whether other modelling techniques should be investigated.

Chapter 4

IMPROVING THE STOCHASTIC USE OF EBSD MODELS

4 Introduction

The reliability of the supply-demand schedules provided in the output by EBSD models can be affected by the random variation of input data due to the natural spatial or temporal variability of both supply and demand. In order to test the reliability of the EBSD model solution, the water industry proposed the 'intermediate framework' (UKWIR, 2002b, UKWIR, 2002a). This framework uses Monte Carlo simulation to determine whether the solution provided by the EBSD models remains valid under uncertainty on supply and demand data. Monte Carlo simulation also provides a measure of the levels of service that the options in the solution should provide. If this is lower than companies' target level of service, then target headroom is increased and the EBSD model is run again to return a new combination of options. Water companies face confusion about how much the headroom values should be increased and this can discourage the application of the framework (see paragraph 1.6.2.4 in the Chapter 1).

To overcome this issue, two possible extensions of the 'intermediate framework' are proposed to extend the model presented in Chapter 2: the '*THR-strategy*' and the '*CUT-strategy*'. In the '*THR-strategy*' the headroom values are increased by the worst, or close to worst, deficits recorded under the Monte Carlo simulation. Under the '*CUT-strategy*' companies' headroom values remain unvaried and instead, at each run of the EBSD model, new constraint equations are introduced that exclude unreliable grouping of schemes identified during previous runs. The results from both methods are analysed and compared and their respective benefits and limitations are discussed.

The Chapter is structured as follows: section 4.1 presents a summary of the model structure; section 4.2 presents the mathematical formulation used to implement Monte Carlo simulation together with the '*THR-strategy*' and '*CUT-strategy*'. Section 4.3 shows the case study and is followed by results in section 4.4. Discussion of results and conclusions are presented in sections 4.5 and 4.6 respectively.

4.1 Summary of model formulation

Graphical representations of the '*THR-strategy*' and the '*CUT- strategy*' are shown in Figure 30. Under both the '*THR-strategy*' and '*CUT- strategy*', the water companies' target level of service (*TLS*) is first defined. *TLS* values are agreed between companies and their customers and set an upper limit to the frequency by which companies anticipate to impose restrictions on supplying water, i.e. no more than 1/N years (see section 1.5.1). This approximates to an annual probability of less than 1/N that supply-demand failures will occur. Then, the EBSD model is run in a two step-process: demands are reduced as little as possible to remove infeasibilities at water resource zones (see section 2.1.7.2, in Chapter 2), then the EBSD model presented in Chapter 2 is run. The EBSD model returns the schedule and optimal extent of use (least-cost quantity) of supply, demand management and transfer schemes that meet the forecast demands at minimum costs.

The reliability (probability of failure) of the EBSD model solution is then tested using Monte Carlo simulation for the dry year critical period scenario (the worst case scenario with higher demands). Probability distribution functions of uncertainty on supply and demand input data are then considered. A number 'm' of possible deviations from the supply and demand input data (uncertainty) are sampled from the probability distribution functions (see Figure 31). The supply-demand balance at each demand node is then tested by adding the uncertain term to the supply and demand estimates (target headroom values are set equal to zero). The probability of supply-demand deficits ($PSF_{i,t}$) is then calculated for each water resource zone *i* and year *t*. This is equal to the ratio between the total number of deficits recorded over the 'm' simulations and total number of simulations *mmax*. If $PSF_{i,t}$ is greater than the company's allowed maximum probability of failure $TLS_{i,t}$, then the EBSD model is run again and the '*THR-strategy*' or the '*CUT-strategy*' is applied, to identify, a different schedule of options. This procedure is repeated 'n' times until a solution is found for which $PSF_{i,t}$ is lower than $TLS_{i,t}$. Under the '*THR-strategy*' target headroom values are increased by the worst, or close to worse, deficit recorded over the Monte Carlo simulation (see section 1.4.5.1). Under the '*CUT-strategy*' target headroom values are not varied but new equations are included in the EBSD model to exclude solutions (supply-demand schedules) selected at previous iterations.

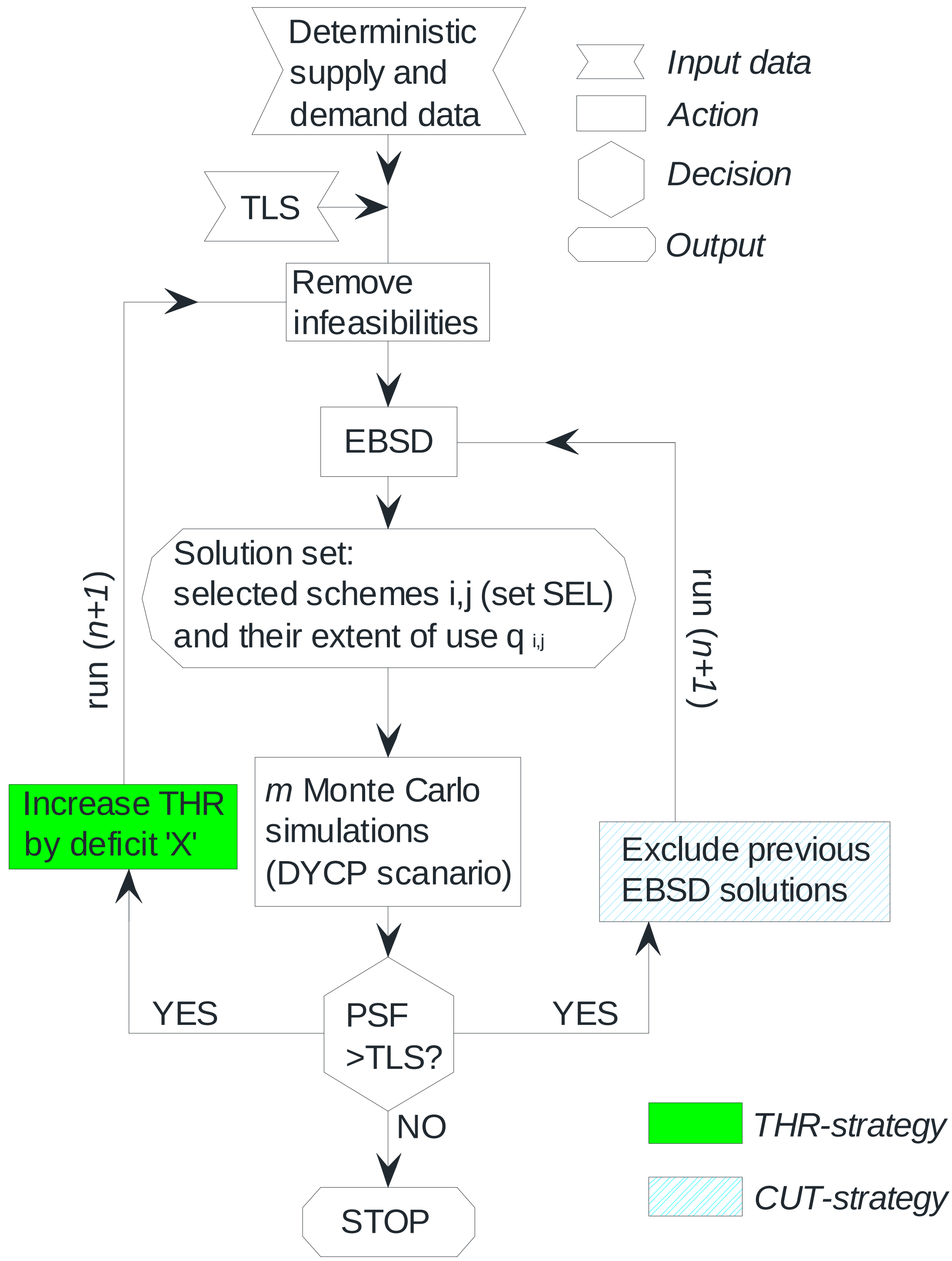

Figure 30: The ‘*THR-strategy*’ and the ‘*CUT- strategy*’.

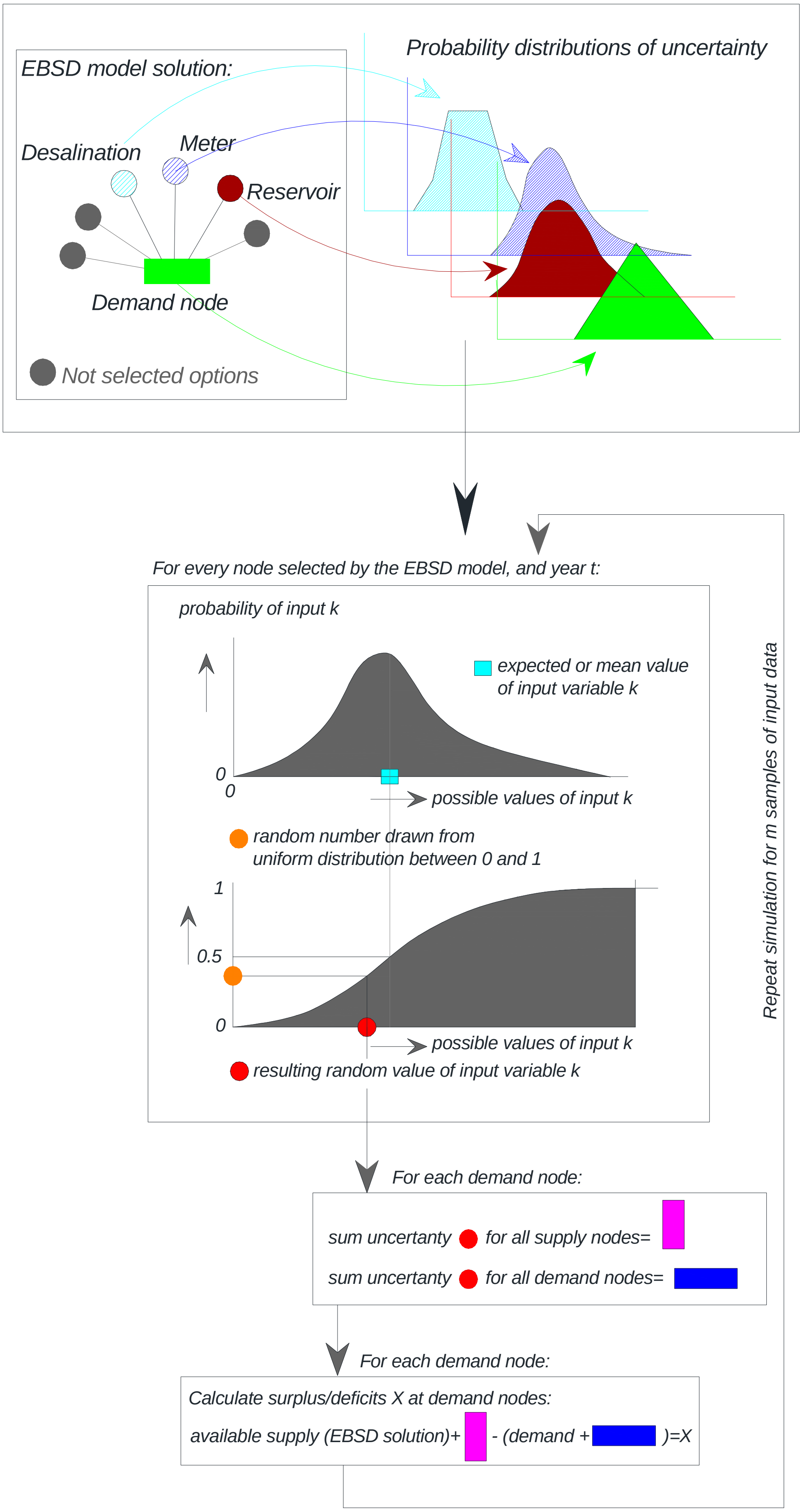

Figure 31: Monte Carlo simulation applied to the solution of the EBSD model.

The model formulation is presented in the following sections. The nomenclature is first introduced in section 4.2.1. Section 4.2.2 describes the formulation adopted to implement the Monte Carlo simulation. The '*THR-strategy*' and the '*CUT-strategy*' are then introduced in sections 4.2.3.1 and 4.2.3.2 respectively.

4.2 Model formulation

4.2.1 Nomenclature

Indices of Sets

m	Monte Carlo iterations
n	EBSD model runs
eq	elements of set EQ indicating the number of times the EBSD model is run

Sets

M	set of Monte Carlo iterations
N	set of the EBSD model runs
SEL	subsets of the Cartesian product between schemes i,j belonging to the connectivity matrix CON and set EQ
DEM	subset of demand nodes i in deficit under the Monte Carlo simulation
EQ	set composed by as many elements eq as the number of times the EBSD model is run $EQ=\{eq1 \ldots eqn\}$.

Parameters

$mmax$	maximum number of Monte Carlo iterations
$U_{i,j,t,m}$	uncertainty value at option (i,j) and Monte Carlo iteration m
$X_{i,t}$	supply-demand balance at demand node i and time t
$count_{i,j,t,m}$	counter for the number of times a supply-demand deficit is recorded ($X_{i,t}$<0) over the m Monte Carlo iterations
$cpdi_{i,j,t}$	distribution input at demand node i, time t under the DYCP scenario
$cpsr_{i,j,t}$	outage allowance at demand node i, time t under the DYCP scenario
$Xrank_{i,t,m}$	deficits at demand node i, time t and Monte Carlo iteration m ranked from the highest to the lowest value
$mf_{i,t}$	maximum number of allowed failures (deficits) at demand node i, time t

$TLS_{i,t}$	target level of service for water resource zone i at year t
$AP_{i,t}$	level of service for the solution set provided by the EBSD model at water resource zone i at year t
$\alpha fix_{i,t}$	maximum level of demand satisfaction at demand nodes i and year t under the dry year critical period scenario

4.2.2 Monte Carlo simulation

4.2.2.1 Uncertainty and correlation

When sampling from probability distribution functions (see Figure 31) it is important to consider possible correlations among the input data values (see also section 1.5.2). This is done through the following steps. A vector of random uncorrelated data ***X*** is first generated. A correlation matrix ***C*** is then defined that specifies the magnitude of the correlation coefficients. ***C*** is a positive definite and symmetric matrix and can be decomposed into a lower triangular matrix ***R*** and its transposition ***R'***. The decomposition ***C=RR'*** is called Cholesky factorisation. Given ***X*** and ***R***, the vector of correlated numbers ***D*** can be calculated as ***D***=***XR'*** (Iman and Conover, 1982, Lurie and Goldberg, 1998). Probability distribution functions of uncertainty on supply and demand data are then defined. The uncertainty values are then estimated from the inverse cumulative distribution functions alongside the random correlated numbers ***D*** (see also illustration in Figure 31).

4.2.2.2 The supply-demand balance under the Monte Carlo simulation

The uncertainty values $U_{i,j,t,m}$ identified over a number m of random samples are added to the supply and demand input data of the EBSD model. This analysis is done for the worst-case scenario (the dry year critical period or DYCP). The supply-demand balance is then evaluated at each demand node by only considering the set of schemes i,j (set SEL) selected by the EBSD model.

$$X_{i,t,m} = \sum_j \left(q_{j,i,t} + U_{j,i,t,m}\right) - \sum_j \left(q_{i,j,t} + U_{i,j,t,m}\right) - cpsr_{i,t} - \alpha\, fix_{i,t} \times \left(cpdi_{i,t} + \sum_j U_{i,j,t,m}\Big|_{i=j} \right) \quad 4.1$$

$$\forall i \in DEM, (j,i) \in SEL, t \in T, m \in M$$

In the equation above $X_{i,t,m}$ is the water surplus (if positive) or deficit (if negative) recorded at year t (set T), demand node i (set DEM) and simulation m (set M). $\Sigma_j\, q_{j,i,t}$ is the sum of flows entering demand node i at year t, while $\Sigma_j\, q_{i,j,t}$ is the sum of flows leaving demand node i at year t. $q_{i,j,t}$ is output by the EBSD model. Terms $cpdi_{i,t}$ and $cpsr_{i,t}$ are the water demand (distribution input) and 'outage allowance' respectively (see section 1.5.1), while $\alpha fix_{i,t}$ is the maximum level of demand satisfaction at demand node i and year t. Equation 4.1 is applied to the dry year critical period scenario. If during any of the 'm' simulations, a deficit occurs ($X_{i,t,m}$<0), a counter $count_{i,t,m}$ is increased by one unit:

$$count_{i,t,m} = count_{i,t,m} + 1 \quad if \;\; X_{i,t,m} < 0 \quad \forall i \in DEM, t \in T, m \in M \qquad 4.2$$

For each year t and demand node i, the ratio between the total number of failures and the total number of simulations is then calculated. If this is greater than the company's accepted maximum probability of failure, the EBSD model is run again, and the '*THR-strategy*' or the '*CUT-strategy*' is applied to identify a new supply-demand schedule.

4.2.3 Generating different solutions

4.2.3.1 The 'THR- strategy'

Under the '*THR-strategy*' the companies' target headroom values are increased according to the following procedure. First, deficits ($X_{i,t,m}$<0) are ranked from the highest to the lowest obtaining the ranked matrix $Xrank_{i,t,m}$. The maximum number of allowed failures ($mf_{i,t}$) is then determined for each demand node i and time step t by multiplying the *nbmax* by the maximum probability of failure $TLS_{i,t}$. The first $mf_{i,t}$ largest deficits are then removed from matrix $Xrank_{i,t,m}$ (e.g. if *nbmax*=100 and $TLS_{i,t}$=5%, then the first 5 largest deficits are removed). Finally the deficit at position $mf_{i,t}$+1 is used to increase the company's target headroom values.

4.2.3.2 The 'CUT- strategy'

Under the proposed '*CUT-strategy*', every time the EBSD model is run, a new set of equations are included in the EBSD model formulation to exclude solutions identified at previous runs:

$$\sum_t \left[\sum_{j \in SEL} \left| AL_{j,i,t} - AL_{j,i,t-1} \right| \right] \leq \left(par_{eq} - 1 \right) \qquad \forall eq \in EQ, i \in DEF \qquad 4.3$$

In the equations above *EQ* is a set composed by as many elements *eq* as the number of times the EBSD model is run, *DEF* is the set of demand nodes i in deficit ($X_{i,t,m}$<0) under the 'm' simulations, while *SEL* is a set containing the list of schemes *i,j* activated each time the EBSD model is run, i.e., $(j,i,eq) \in SEL$.

Equation 4.3 works in the following way: every time the EBSD model is run a new combination of schemes '*A*' is found. Then, if '*A*' fails under the Monte Carlo analysis, the EBSD model is run again and equation 4.3 is used to exclude solution '*A*' from the next model solution '*B*'. If '*B*' is unsuccessful under the Monte Carlo simulation (i.e. its level of service is lower than the target), this solution is saved in set *SEL* together with solution '*A*', i.e., *SEL= {'B'.eq2, 'A'.eq1}*. This procedure is repeated until a combination of schemes is found that is successful under the Monte Carlo simulation. Parameter par_{eq} is the number of schemes (selected nodes and links in set *SEL*) activated at each iteration. The difference (par_{eq}-1) implies that every time the EBSD model is run, a new solution (grouping of options) has to be found that differs from all previous solutions (e.g. '*A*' and '*B*') by at least one option.

Figure 31 below provides a detailed flow chart of the '*THR-strategy*' and the '*CUT-strategy*'.

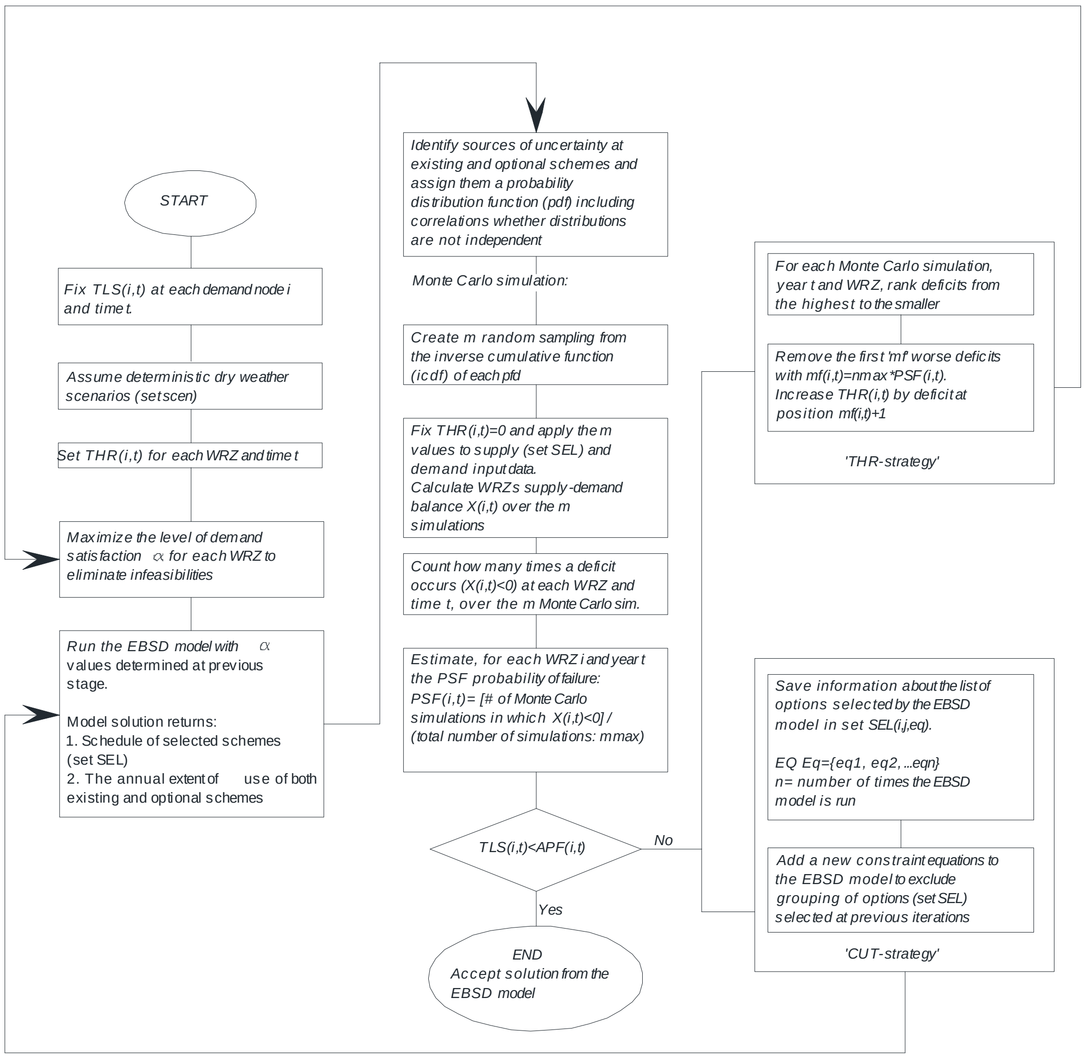

Figure 32: Schematic chart flow of the '*THR-strategy*' and '*CUT-strategy*'.

4.3 Case Study

The '*THR-strategy*' method was developed for the WRSE group. The work was intended to be applied to the whole WRSE area (34 water resource zones, see Chapter 2) starting from a sub-set of the WRSE network composed of only three water resource zones. This pilot network is shown in Figure 33. Each water resource zone of network in Figure 33 belongs to a different water company.

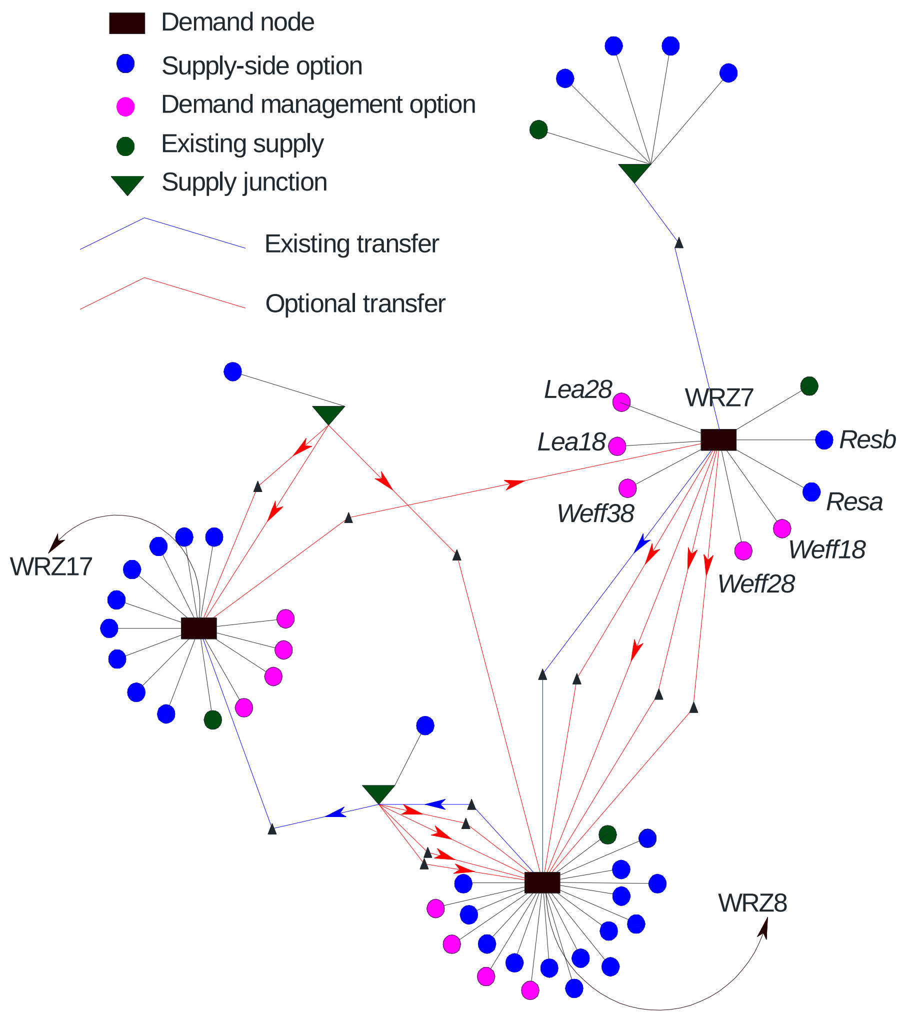

Figure 33: Network topology.

The '*CUT-strategy*' was also applied to network in Figure 33. A 26 year planning horizon was considered. The input data (supply and demand estimates, headroom values, target level of service, costs, probability distribution functions etc.) are confidential and were randomly varied between +10% and -10%. Four demand scenarios (DYAA, DYCP, NYAA and MDO) were considered as in Chapter 2. One thousands Monte Carlo simulations were applied.

The probability distribution functions in this case study are triangular, uniform and normal (first column of Table 34) and are extrapolated from company water resources management plans. Column 'HU' of Table 34 provides the list of the uncertainty types (see headroom components in section 1.5.2) applied to the existing nodes (suffix '*EXDO*'). All remaining columns in Table 34 ('lower limit', 'mode', 'upper limit', 'mean', 'standard deviation') provide the statistics for each probability distribution function.

Distribution	HC	Node	Lower limit	Mode	Upper limit	Mean	Standard deviation
Triangular	*S6*	*ExDO7*	-3	2	4	/	/
Normal	*D1*	*WRZ07*	/	/	/	0	0.73
Triangular	*D2*	*WRZ07*	-6	0	6	/	/
Triangular	*D3*	*WRZ07*	-2	0	3	/	/
Triangular	*D8*	*WRZ07*	-8	0	7	/	/
Uniform	*S5*	*ExDO8*	1.68	0	9.58	/	/
Triangular	*S6*	*ExDO8*	-1.3	1	1.3	/	/
Triangular	*S8*	*ExDO8*	-1.5	3	8	/	/
Triangular	*D1*	*WRZ8*	-0.74	-0.74	0	/	/
Triangular	*D2*	*WRZ8*	-4	0	8	/	/
Triangular	*D3*	*WRZ8*	0.9	1.4	1.9	/	/
Uniform	*S8*	*ExDO5*	4	0	5	/	/
Triangular	*D1*	*WRZ17*	-8	0	9	/	/
Triangular	*D2*	*WRZ17*	-4	0	8	/	/
Triangular	*D3*	*WRZ17*	-1.2	0	1.2	/	/

Table 34: Probability distribution functions assigned to different uncertainty components (S5, S6, S8 for the existing supply nodes, D1, D2 and D3 for the demand nodes).

For the optional schemes, a normal probability distribution function of uncertainty was applied with a mean of zero and standard deviation of 0.02 based on (EA, 2010a). The correlation coefficients (Table 35) were assumed by following the UKWIR guidelines (UKWIR, 2002c).

		Correlation coefficient
S8 -'*EXDO17*'	D3 - '*WRZ07*'	0.75
S8 - '*EXDO38*'	D3 - '*WRZ8*'	0.75
S8 - '*EXDO35*'	D3 - '*WRZ17*'	0.8
S9 - '*sop068*'	S9 - *sop120*'	0.6
S9 - '*sop079*'	S9 - '*sop197*'	0.6

Table 35: Correlation coefficients.

Uncertainty types S8 and D3 are positively correlated (UKWIR, 2002c). This is because if climate change (uncertainty type S8) has an impact on yields, then it will also likely impact the level of water demand (uncertainty type D3). Annual water demand is generally driven by summer consumption while supply mostly depends on rainfall. Instead of considering a correlation coefficient equal to one between the two (suitable for directly correlated uncertainties), a lower value of 0.75 was adopted following (South East Water, 2014). The optional groundwater sources (‘*sop068*’, ‘*sop120*’ in *WRZ17* and ‘*sop079*’, ‘*sop197*’ in *WRZ8*) are subject to uncertainty type S9 and are positively correlated by a factor of 0.6 (UKWIR, 2002c). Groundwater schemes in the same water resource zone are assumed to be affected by the same sustainability reductions (e.g. licence reductions).

4.4 Results

Both methods (‘*THR-strategy*’ and ‘*CUT-strategy*’) are implemented in GAMS and solved with CPLEX on a DELL Precision 7500 machine with 24 GB RAM. Table 36 shows the model statistics for both runs.

	Model statistics	
	‘THR-strategy’	*‘CUT-strategy’*
Run time	34 seconds	1 minute
Relative gap reached under all iterations	0%	0%
Total number of variables	16,387	16,309
Binary variables	1,298	1,281

Table 36: Models statistics for the ‘*THR-strategy*’ and the ‘*CUT-strategy*’.

Two iterations were required under the ‘*THR-strategy*’, three under the ‘*CUT-strategy*’. Of the three water resource zones (‘*WRZ7’*, ‘*WRZ8*’ and ‘*WRZ17’*, see Figure 31), only ‘*WRZ7’* has deficits over the Monte Carlo simulations. The remaining tables and figures only refer to water resource zone ‘*WRZ7’*.

The ‘*CUT-strategy*’ and the ‘*THR-strategy*’ identify the same schedule of schemes for zone ‘*WRZ7*’: reservoirs ‘*Res_b’* and ‘*Res255’* and a water efficiency option ‘*Weff28’* for the water resource zone. Table 37 shows the total discounted cost of the solutions obtained under the ‘*CUT-strategy*’ and the ‘*THR-strategy*’, for each iteration. Total costs include: capital expenditure, and fixed and variable operating costs. The latter are weighted over the four demand scenarios (dry year annual average DYAA, dry year critical period DYCP, minimum deployable output MDO, and normal year annual average NYAA).

	Total cost [£M]	
Solution Set	'*THR-strategy*'	'*CUT-strategy*'
Initial Solution - Iteration 1	81.1	81.1
Iteration 2	86.2	81.3
Iteration 3	/	82.1
Iteration 4	/	82.3
Iteration 5	/	82.7
Iteration 6	/	83.1

Table 37: Total discounted costs in £M (capital expenditure plus fixed and variable operating costs) for solutions obtained at each run of the EBSD model, under both the '*CUT-strategy*' and '*THR-strategy*', for water resource zone '*WRZ7*'.

Total costs under the '*THR-strategy*' (see the last iteration number 2) are higher than those under the '*CUT-strategy*' (Table 37). This is because, with the '*THR-strategy*', target headroom values are increased by deficits generated in the Monte Carlo simulation (Figure 34). This increases the extent of use of the selected schemes, and consequently the variable cost element.

Figure 34 shows the target headroom profile for water resource zone '*WRZ7*' under the '*THR-strategy*' (the headroom values remain unchanged under the '*CUT-strategy*'). Target headroom values increase in the second iteration, towards the end of the planning period, starting from year 2027, corresponding with a demand increase of 26 Ml/d. i.e. from 50 Ml/d, in the previous year, to 76 Ml/d.

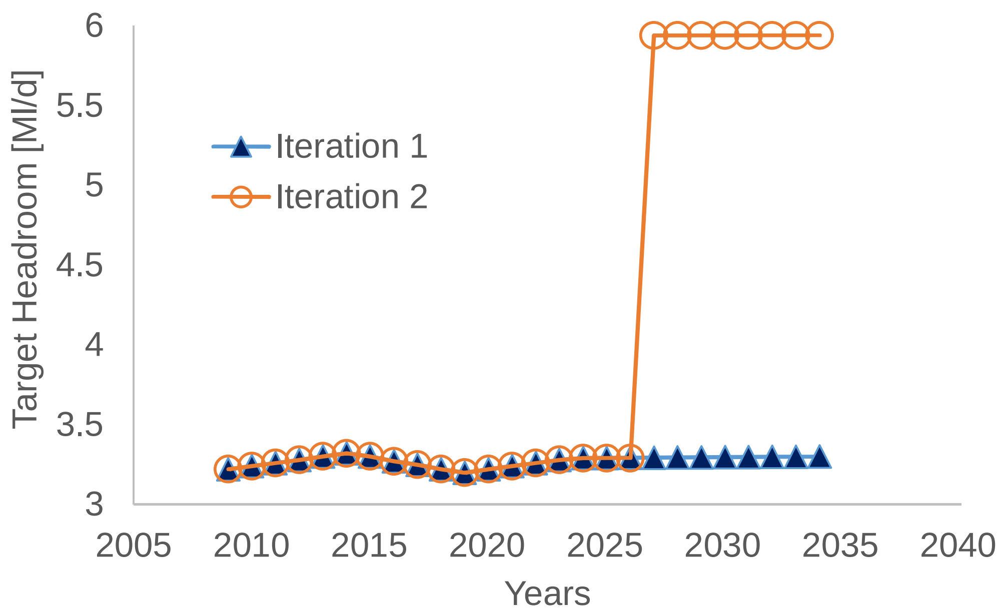

Figure 34: Target headroom values at each run of the EBSD model, under the '*THR-strategy*'.

Figure 36 shows, for the '*THR-strategy*' (Panel 'a') and the '*CUT-strategy*' (Panel 'b'), the annual probability of failure at each iteration for water resource zone '*WRZ7*'. A maximum allowed probability of system failure of 0.1 (see purple line in Figure 36) was considered. The system probability of failure (identified with the Monte Carlo simulation) exceeds the 0.1 threshold (under both the '*THR-strategy*' and the '*CUT-strategy*') after year 2026 due to the increased level of demand.

The probability of failure simulated over the last iteration (iteration 2 for the '*THR-strategy*' and iteration 6 for the '*CUT-strategy*') is higher for years 2023 to 2026 (Figure 35 and Figure 36) compared to previous iterations. This is because, most of the demand management options selected in previous iterations (two in year 2023 and two in year 2024) are replaced by demand management scheme '*Weff38*' in year 2025. The extent of use of the existing node is also increased over years 2023 to 2026 (by a maximum of 0.29 Ml/d). Reservoir '*Res_b'* is only activated in year 2027. Since the level of failure is calculated based on the schemes' maximum capacity (demand management options savings are accounted from their first year of activation), the level of surplus in years 2023 to 2026 is lower than in previous iterations.

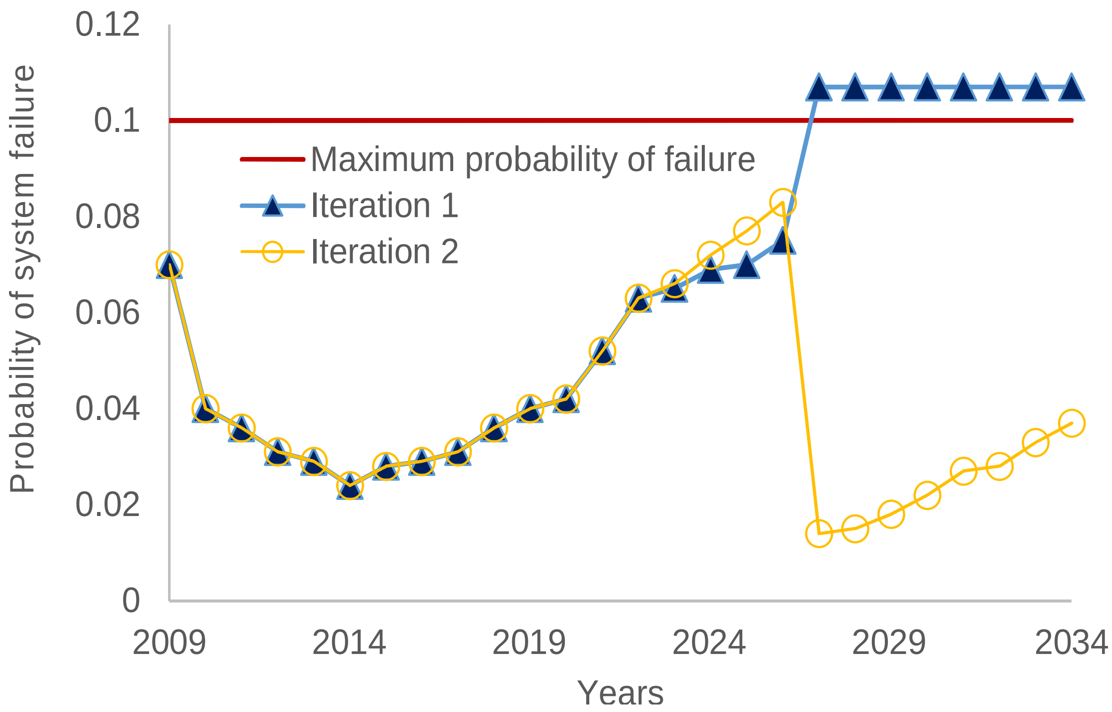

Figure 35: Supply-demand resources system probability of failure (blue and orange lines) and maximum probability of failure (horizontal red line) for water resource zone '*WRZ7'* under the '*THR-strategy'*.

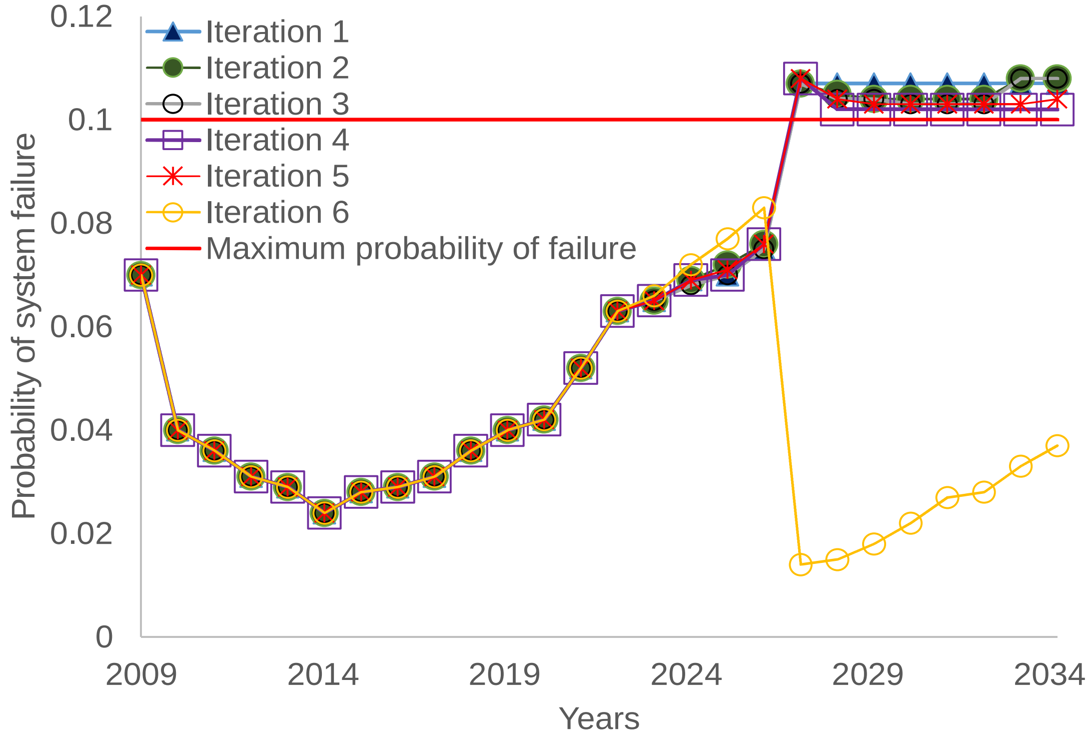

Figure 36: Supply-demand resources system probability of failure (blue and orange lines) and maximum probability of failure (horizontal red line) for water resource zone '*WRZ7*' under the '*CUT-strategy*' (panel 'b').

Figure 37 shows, for the '*THR-strategy*' and '*CUT-strategy*', the extent of use of schemes selected at each iteration under the dry year critical period scenario. Under the '*CUT-strategy*' the model consistently selects, over the first five iterations, reservoirs '*Res255*' and '*Res256*' while varying the combination of selected demand management options. At the final iteration, reservoir option '*Res_b'* is implemented. This scheme provides a maximum capacity of 21 Ml/d, much higher than the maximum saving (0.32 Ml/d) with available demand management schemes. This increases the level of surplus in the network and consequently reduces the frequency of supply-demand deficits generated under the Monte Carlo simulation. Specifically the probability of failure decreases from 0.08 in year 2026 to 0.014 in the following year (see Figure 36). After year 2027, the probability of failure increases (up to a maximum of 0.04 in year 2034), due to an increased level of demand.

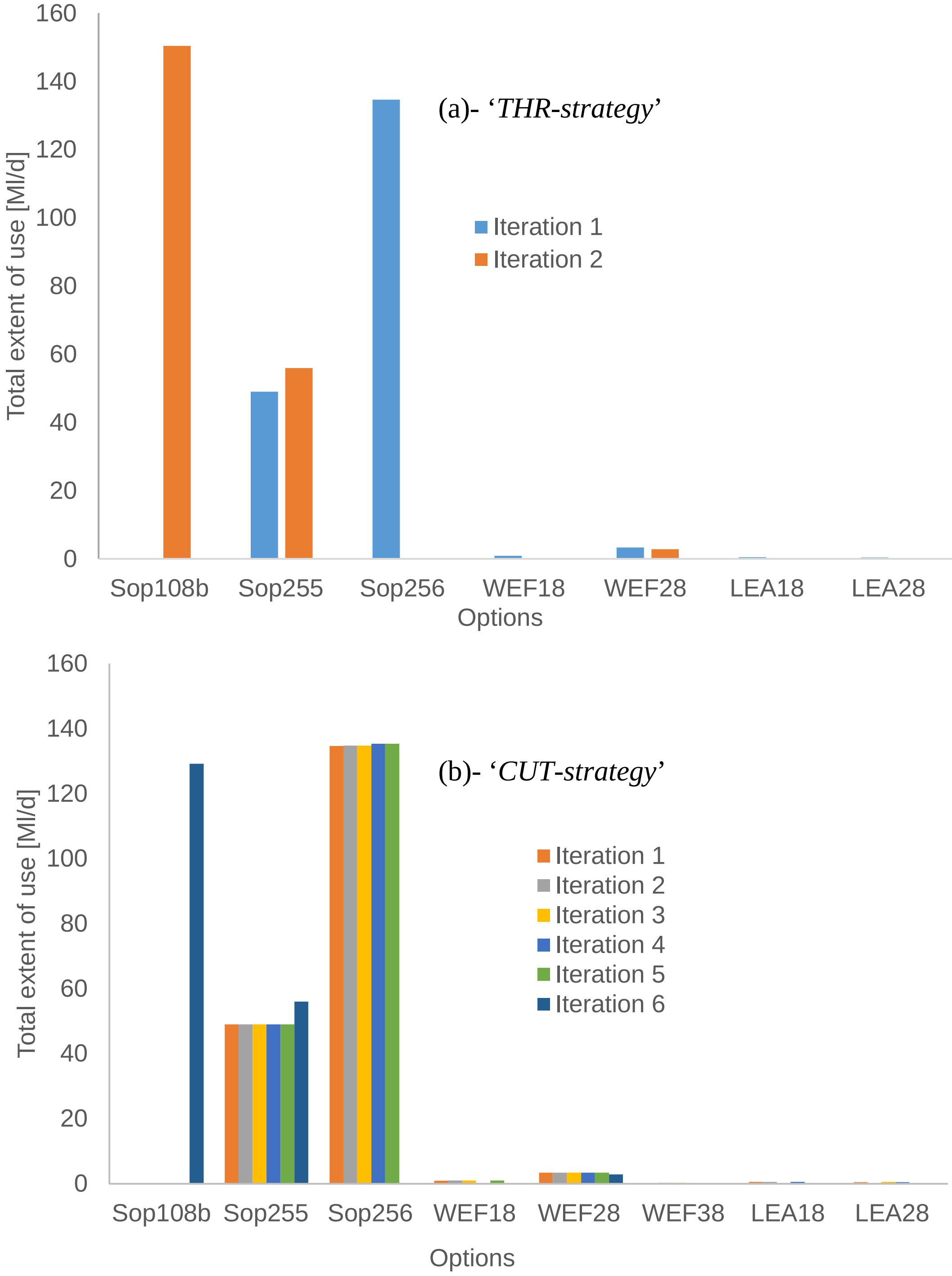

Figure 37: Least cost quantity of selected schemes under the ‘*THR-strategy*’ (top panel ‘a’) and ‘*CUT-strategy*’ (bottom panel ‘b’), for the DYCP scenario and ‘*WRZ7’* only.

4.4.1 Sensitivity analysis- adding another node to the analysed network

Reservoir ‘*Res_b’* reduces the system probability of failure below the company target level (see Figure 36). If, however, its implementation raises environmental or political issues, the water company may decide to abandon the scheme. By increasing the company’s target headroom values, the ‘*THR-strategy*’ may overlook solutions that are lower cost, still reliable, and preferred by planners for reasons that cannot be fully represented in the model (see also Appendix II). On the contrary, the '*CUT-strategy*' does not overlook any portfolio.

This is demonstrated by adding in the analysed network (Figure 33) and additional node ('*Res_c*') for water resource zone '*WRZ7*'. This node has lower capital and operating costs than '*Res_b*', and a maximum capacity of 17 Ml/d (see Table 38).

	Capital expenditure [£M]	Fixed operating cost [k£]	Variable operating cost [pence/m^3]	Maximum capacity [Ml/d]
'*Res_b*'	525	344	30	17
Res_c'	425	244	19	21

Table 38: Comparison of undiscounted costs and maximum capacity of schemes '*Res_b*' and '*Res_c*'.

The '*THR-strategy*' returns the same solution as in Figure 37, with selected options reservoirs '*Res_b*', '*Res255*' and the water efficiency measure '*Weff28*'. Under the '*CUT-strategy*', the model selects (at the last iteration number 6) reservoir '*Res_c*', '*Res255*' and the water efficiency option '*Weff28*' (the first five iterations identify the same schedule of schemes as in Figure 37). The system probability of failure (Figure 38) is higher than with selection of option '*Res_b*' (Figure 36) but still below the maximum probability of failure (0.1, see red line in Figure 38). This is due to the lower maximum capacity of '*Res_c*' compared to '*Res_b*'.

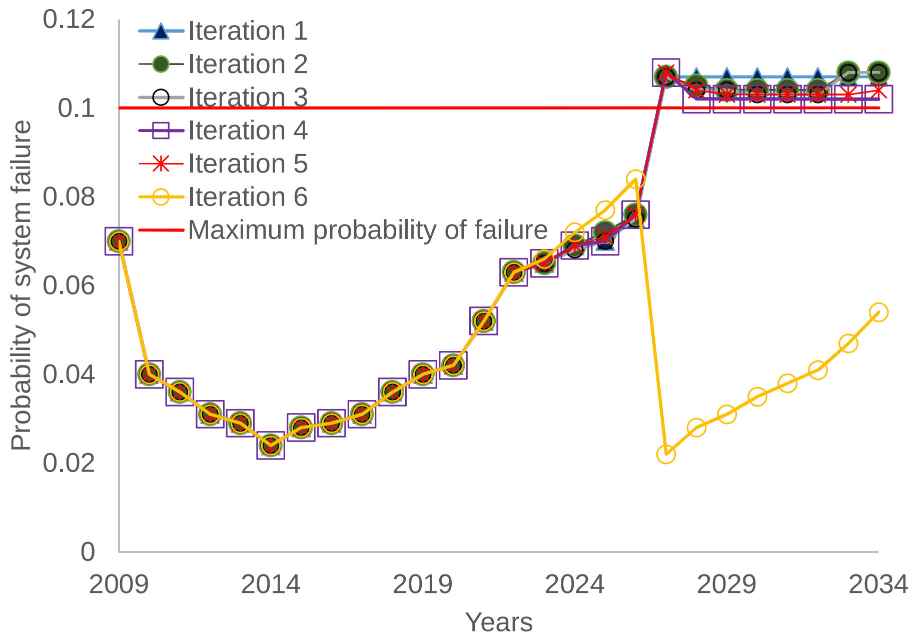

Figure 38: Probability of failure under the '*CUT-strategy*' when scheme '*Res_c*' is added to the modelled network, for water resource zone '*WRZ7*'.

4.4.2 Testing reliability over a diverse set of near-optimal solutions with the '*CUT-strategy*'

The '*CUT-strategy*' can also be used to return a diverse set of schemes (portfolios) and their associated level of service. As specified in Appendix II, given uncertainty around projected scheme capital and operating costs and the inability of EBSD models to embed non-monetary metrics of system performance (see also section 1.6.2.7), the least-cost solution may not represent, necessarily, the 'best' solution to the problem. For these reasons, regulators and water company decision makers may prefer diverse plans that are sufficiently 'close' the least-cost plan. The '*CUT-strategy*' allows the identification of these plans and their associated reliability. This is shown in Figure 39 below, where the '*CUT-strategy*' has been used to obtain 15 alternative solutions (schedule of schemes). The red line with red dots corresponds to the solution identified by the '*THR-strategy*' (see iteration 8 in Figure 37), while the green line with green dots is the first reliable lower cost solution identified by the '*CUT-strategy*' (see iteration 2 in Figure 37 and iteration 6 in Figure 38). In iteration 14 and 15, the activation in year 2027 of a reservoir '*Res_a*' (maximum capacity of 10 Ml/d) and its conjunctive use with reservoir 'sop256' (maximum capacity of 22 Ml/d) reduces the probability of failure to 0.001 from 2027 to 2033, and 0.002 in 2034.

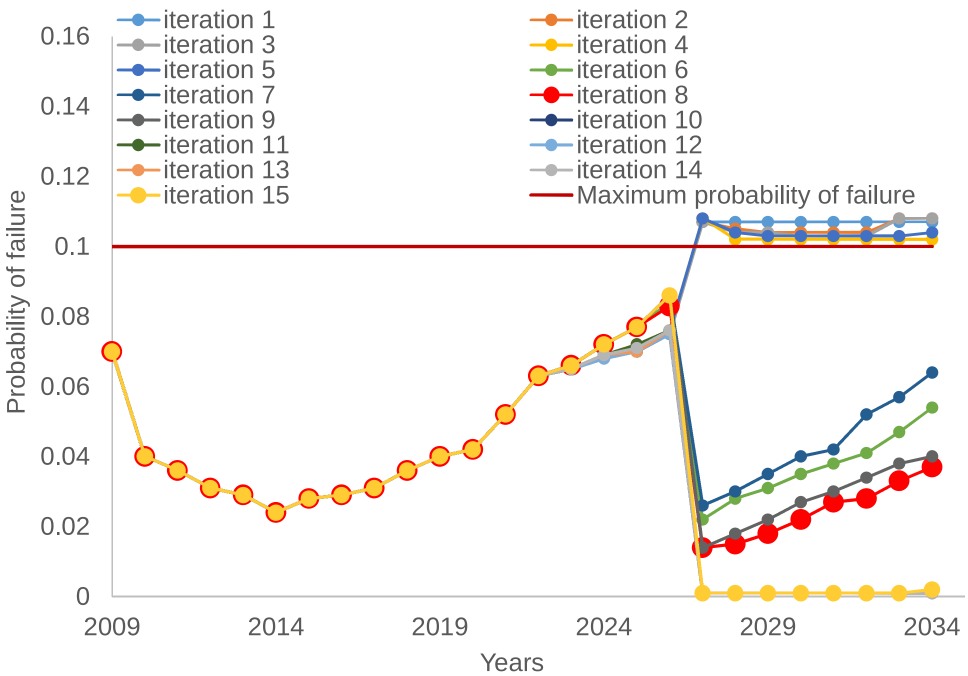

Figure 39: Probability of failure over a range of near-optimal solutions

Figure 40 shows the minimum (light orange dots), maximum (dark orange) and average (red dots) probability of failure recorded over the planning horizon, for the 15 portfolios identified under the '*CUT-strategy*'. Each of the 15 dots (see numbers next to the red dots) represent a unique portfolio of schemes. The company decision makers may opt to adopt higher-cost solutions (i.e. those in iterations 7, 9 or 10) than the lower-cost solution identified with the '*CUT-strategy*' (see iteration 6 in Figure 40) or the '*THR-strategy*' (see iteration 8). This could happen, if solutions 7, 9 or 10 present other benefits (non-monetary metrics) not represented in the model, which are important to the decision maker.

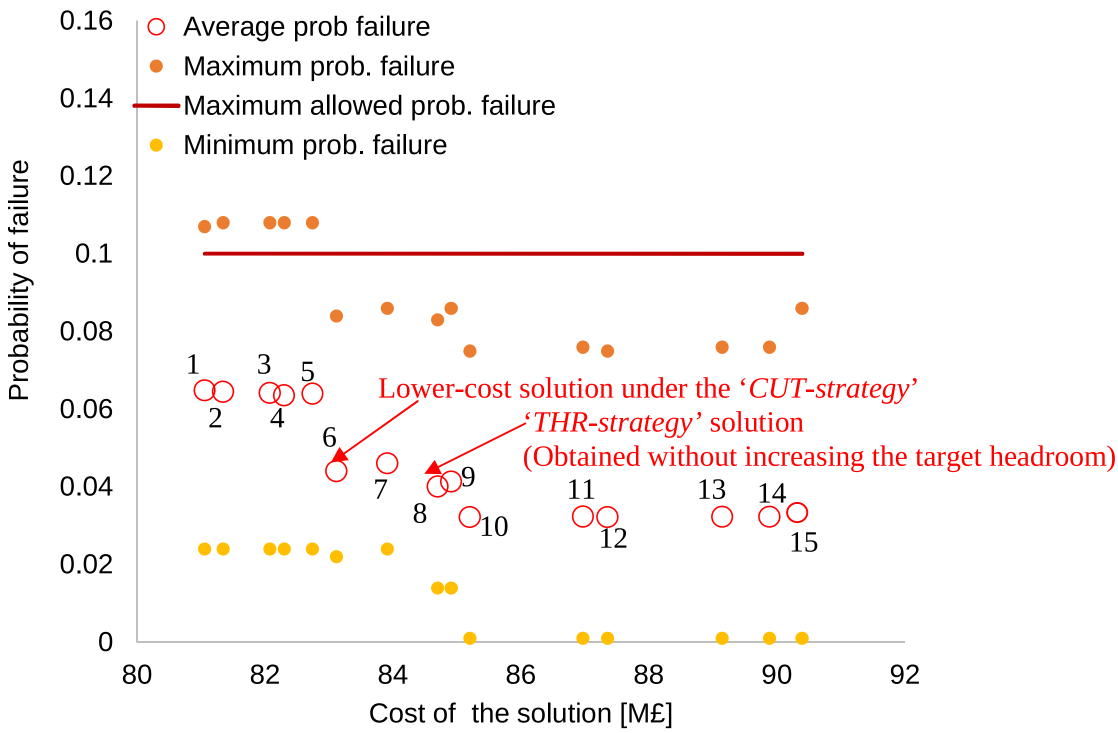

Figure 40: Minimum (light orange dots), maximum (dark orange) and average (red dots) probability of failure over the near-optimal solutions identified with the '*CUT-strategy*'.

Figure 43 shows the extent of use of schemes selected over the 15 near-optimal solutions identified with the '*CUT-strategy*'.

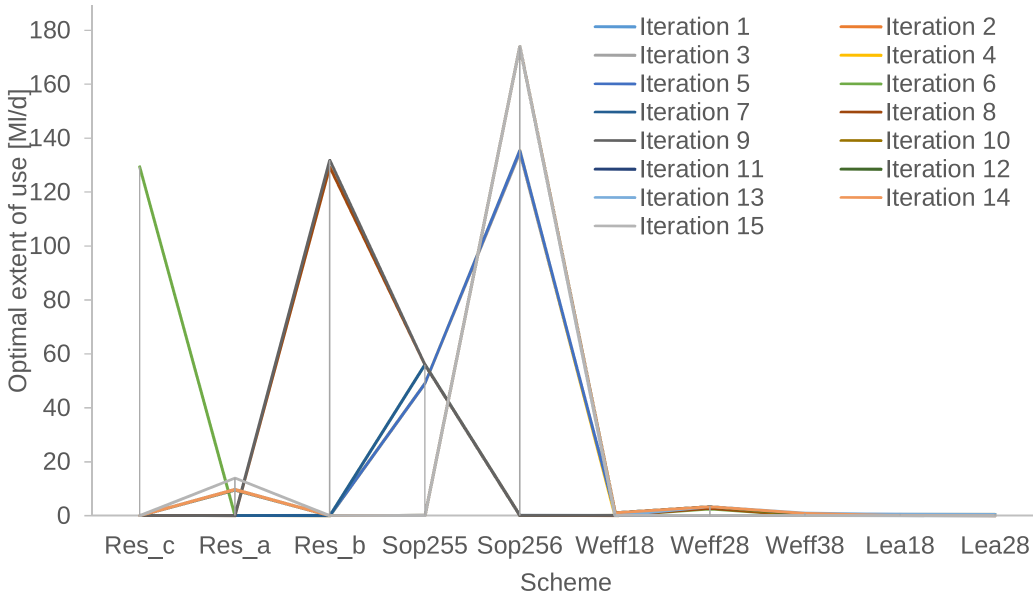

Figure 41: Optimal extent of use of schemes selected over the near-optimal solutions identified with the '*CUT-strategy*'.

4.5 Discussion

This Chapter proposes two extensions to the EBSD 'intermediate framework': the '*THR-strategy*' based on current guidelines (UKWIR, 2002c) and the '*CUT-strategy*' developed in this thesis. Both strategies consist of an iterative approach where the EBSD model is run and the reliability (probability of failure) of the model solution (supply-demand schedules) is tested using Monte Carlo simulation. Monte Carlo simulation consists of sampling 'm' random values of uncertainty from the estimated probability distribution functions and applying these values to the supply and demand data. The supply-demand balance is evaluated over the 'm' simulations at a water resource zone level. If a level of service is found which is lower than the target one, then the EBSD model is run again to return an alternative combination of schemes. Under the '*THR-strategy*' target headroom values are increased by the worst deficits recorded over the Monte Carlo simulation. If the increased target headroom values generate infeasibilities in the modelled network, then the target headroom values are reduced just enough to remove the network infeasibilities. Under the '*CUT-strategy*' target headroom values remain unchanged and new constraints are added to exclude unreliable solutions selected at previous iterations. Limitations of the two methods are listed below.

The '*THR-strategy*' may generate network infeasibilities if demand becomes higher than the available supply from existing and optional schemes (due to the increased level of target headroom). Furthermore, increasing the headroom values may trigger the model to activate unnecessary infrastructure. It is possible that under a slightly lower deficit, the model would return a lower-cost, but still reliable solution. This is demonstrated by adding a new node to the modelled network that has lower costs than the one selected under '*THR-strategy*' as well as a lower maximum capacity (by 4 Ml/d). The selection of this node, can still bring the network level of failure below the allowed level of failure. However, with the '*THR-strategy*' this scheme cannot be selected since its maximum supply (in conjunction with supply from other selected schemes) is not sufficient and cannot meet the increased level of demand (due to the augmented values for the target headroom).

The '*THR-strategy*' presented in this Chapter was developed for the WRSE group. A lesson was learned, in that re-evaluating headroom values discourages the application of the 'intermediate framework'. Results from the '*THR-strategy*' stopped at a specific level of target headroom and both companies and regulators struggled to see how the new headroom values would have fitted within the regulatory framework since the target headroom estimates follow established regulatory guidelines (UKWIR, 2002d). The WRSE group did not accept the new headroom values and only considered the fully deterministic version of the EBSD framework referred to as 'current framework' (see model in Chapter 2).

To overcome the limitations above a new iterative procedure (the '*CUT-strategy'*) was formulated, as described in this Chapter. The '*CUT-strategy'* allows identifying a reliable set of schemes without having to modify the company's headroom values at each iteration. This is done by adding new constraints to the model formulation, in order to exclude unreliable solutions identified at previous iterations. The resultant solution differs from those produced at previous iterations by at least one activated option. The '*CUT-strategy*' guarantees the identification of all possible reliable portfolios of schemes contrary to the '*THR*-strategy'. An extension of the '*CUT-strategy*' is also presented: a set of diverse near optimal solutions is generated whose level of reliability is higher than the company's target level. Given uncertainty on projected scheme costs and the inability of the EBSD models to embed non-monetary metrics of the system performance, that can be important to decision makers, it becomes important to be able identify a set of near-optimal reliable solutions (in addition to the lower-cost solution).

The '*CUT-strategy*' is similar to, but not identical to another optimisation technique known as 'modelling for generating alternatives' (see the literature review in Appendix

II). This optimisation technique (Brill et al., 1990) identifies alternative solutions that are maximally different (see Section II.2). This means that at each iteration, the solution is as different as possible from the one at all previous iterations, given minimum targets on the value of the objective function. In the extreme case, the ‘modelling for generating alternatives’ method may return a plan that is completely different (in terms of selection of schemes) than previous solutions. The ‘*CUT-strategy*’, in contrast, identifies at each iteration, the next ‘best’ (in terms of cost) least-cost solution. That is, it finds solutions (portfolios of schemes) whose cost increases progressively. The ‘*CUT-strategy*’ stops when a solution is found with a level of service lower than the target one. This is implemented because water companies in England must show to regulators that their plans are least-cost and it is therefore important to be able to identify solutions that are reliable but also sufficiently ‘close’ (in terms of costs) to the least-cost plan.

A drawback of the ‘*CUT-strategy*’ method is that it may require more iterations than the ‘*THR-strategy*’. The number of iterations may increase if the network expands and this may increase the total run time. To reduce the number of iterations, a minimum level of diversity of two or more schemes could be imposed. However, this may prevent the model from finding possible lower cost solutions or may create infeasibilities in cases where there are too few available options to guarantee an appropriate level of diversity.

4.6 Conclusion

The work presented in this Chapter is an extension of the EBSD ‘intermediate framework’ and the techniques here presented are intended to overcome difficulties that have discouraged its application in real-word planning studies (see also section 1.6.2.4). Two possible extensions of the ‘intermediate framework’ are proposed and compared: the ‘*THR-strategy*’ that follows current regulatory guidelines (UKWIR, 2002c) and the ‘*CUT-strategy*’ proposed in this thesis.

The ‘intermediate framework’, by re-evaluating companies’ headroom values, has led to some confusion, which has generally discouraged its application. This is because headroom estimates follow well established regulatory guidelines (UKWIR, 2002a, UKWIR, 2002b). Increasing target headroom can also generate model infeasibilities, if the level of demand (the distribution input plus the new headroom values) is higher than the available supply from both the existing and the optional schemes. Furthermore, since the new headroom values induce the model to activate new schemes, the model may overlook lower cost solutions that are still reliable.

The '*CUT-strategy*' allows, instead, the identification of reliable set of schemes (portfolios) without having to modify water company target headroom values. It consists of an iterative procedure where, at each iteration, a set of equations is added to exclude non-reliable sets of schemes identified at previous iterations. The '*CUT-strategy*' can be used to return not only the lower-cost reliable portfolio of schemes but also a diverse set of reliable plans. This is implemented to provide water company decision makers with a wider range of options (in addition to the lower-cost one) so a reliable plan can be chosen from among the options whilst considering non-monetary metrics that cannot be represented in the model (see also Appendix II).

In this Chapter, both the '*THR-strategy*' and the '*CUT-strategy*' are applied to the same pilot network and return the same schedule of schemes. When the network is expanded with an additional node, the '*CUT-strategy*' is able to return a reliable lower cost solution than the one identified under the '*THR-strategy*'. This is because under the '*THR-strategy*' the activation of schemes is triggered by increased levels of target headroom values, contrarily to the '*CUT-strategy*'.

The '*CUT-strategy*', because of its ability to overcome the limitations of the 'intermediate framework', could be used by the water industry in place of or in conjunction with the 'intermediate framework'.

Chapter 5

MODELLING REGULATED WATER UTILITY INVESTMENT INCENTIVES

5 Introduction

This Chapter models the infrastructure investment choices of privatised water utilities subject to the rate of return and price cap regulation. The goal is to help understand how regulations may influence water company investment decisions such as their desire to construct transfers with neighbouring companies. Under the 2010-14 regulatory process, water companies in England can make a profit by reducing their operating costs below the regulatory assumptions, or if the allowed rate of return is greater than the market cost of capital. If companies invest in capital cost intensive schemes the associated expenditure is added to their regulatory capital value (total value of assets at privatisation and subsequent investments in new and replacement assets), on which they can earn a return. No such return is earned on the operating expenditure. The regulator also uses incentive schemes to reward (or penalise) companies for overspending (or spending less) on the capital and operating expenditures.

This Chapter is organised as follows. Before proceeding with the literature review and presenting the detailed model formulation, section 5.1 explains the model formulation and how the 'capital bias' is revealed. Section 5.2 presents the literature review, while section 5.3 describes the regulated English water supply sector. The model formulation is presented in section 5.4 and 5.5, and its application is explained in 5.6. Discussion on the model input data is presented in section 5.7 while results are shown in section 5.8. Finally, the model benefits and limitations are presented in section 5.9, followed by conclusions in section 5.10.

5.1 Summary of the model formulation and how it can reveal a 'capital bias'

In this Chapter a new model formulation is introduced to represent how, under the 2010-14 regulatory constraints, water companies in England are allowed to make profit based on the investments they make. Water companies in England are natural monopolies and as such they tend to overprice and under-produce in order to maximise their profit (Budds and McGranahan, 2003). In order to refrain their monopoly market power, the regulator caps the maximum price that companies can charge to customers and on the allowed rate of return for future capital cost expenditures.

From the prospective of the regulator, the best case scenario is one in which cost efficiency is achieved under the regulatory regime. This would mean that company investment decisions are least-cost and this is reflected in lower customer bills. This ‘best case’ scenario is identified in this Chapter by running the EBSD model introduced in Chapter 2 referred to here as the ‘Min Cost’ model run. Given a list of possible future capacity expansions (new supply-side schemes, demand management measures and transfers), the ‘Min Cost’ model identifies the least-cost schedule of schemes that needs to be implemented to meet forecasted future demands under practical, political and environmental restrictions (see the model constraints in Chapter 2). The ‘Min Cost’ model is applied to a water company in the South East of England, a subset of the WRSE network presented in Chapter 3.

The success in delivering the ‘best case’ efficiencies and social benefits (represented with the ‘Min Cost’ model) however depends on the incentives that the regulator uses to ensure cost cutting and quality enhancement. If the regulatory incentives are not well designed companies will not be incentivised to minimise costs and instead over-invest in new infrastructure in order to increase profits. A ‘capital bias’ has been observed in the English privatised water system (Ofwat, 2011, Severn Trent Water, 2010). Such a bias occurs when capital cost-based schemes are chosen inappropriately by water companies, in lieu of more cost-effective solutions that require higher operating costs but lower totals costs (capital and operating costs). The 2010-14 regulatory framework could create a new or contribute to an existing ‘capital bias’ if under the system of incentives water companies profit more by increasing capital expenditure rather than by operating expenditures. The aim of the work presented in this Chapter is therefore to understand if the 2010-14 regulatory mechanisms could possibly drive companies towards inefficient behaviours and generate a ‘capital bias’.

A new model formulation was developed and referred to here as ‘Max Profit’. The ‘Max Profit’ model is applied to the same network used to run the ‘Min Cost’ model. Both models suggest what schemes must be activated (amongst those proposed by the companies) and during which year in the planning horizon, such that the total supply provided by these schemes (together with the existing one) is equal to the company's forecasted annual demand. In 'Max Profit' the schemes are selected in order to maximise the company's profit under the 2010-14 regulatory incentives, while in 'Min Cost', schemes are selected so that the total cost of future capacity expansions is minimised. The incentive schemes that regulators use to induce companies to reduce their capital and operating expenditures below the regulatory assumptions (out performance) are also represented in the 'Max Profit' model formulation. These incentives are included in the company' profit equation and through additional model constraints. The profit equation represents mathematically how companies can make profit under the 2010-14 regulatory system through the investments they make by out-performing the regulatory assumptions on the cost of capital (allowed rate of return) and on the operating expenditure. Companies also receive financial penalties/rewards for under- or out-performing the regulatory allowances on the two costs types. These incentives increase (in case of out-performances) or decrease (for under-performances) company profit and are optimised in the model by introducing new decision variables and model constraints. These incentives include the Capital Incentive Scheme (CIS) scheme and the rolling incentive allowances for the operating costs (here referred to as IAJ). Under the CIS scheme, the regulator makes assumptions about the water companies' future capital expenditures needed to deliver the required level of service at each periodic review period. If water companies spend more than what was assumed (under-performance), the additional capital expenditure is added to their regulatory capital value at the next periodic review period and a financial CIS penalty is subtracted from the revenue allowance. On the contrary, if water companies out-perform the regulatory assumption on the capital costs, then a CIS reward is applied. Under the IAJ scheme, companies receive a reward for lowering the operating costs below the regulatory allowance. Such rewards can be kept for six years before being transferred to customers through lower bills (and consequently lower profits).

The solution of the 'Max Profit' model (schedule of scheme activation over a 26 year planning horizon) is then compared to the one previously obtained by running the 'Min Cost' model. By comparing the schemes selected by the 'Max Profit' and 'Min Cost' models, a 'capital bias' in the regulatory system can be revealed. For example, if under the 'Max Profit' model, capital cost intensive reservoir schemes or desalination plants are selected in place of more operating cost intensive but overall more cost-effective options (as revealed by the 'Min Cost' model) such as imports or demand management measures, water companies can increase their profits by increasing their capital expenditure. This would show that the 2010-14 regulations promote a ‘capital bias’.

Sensitivity analysis is then applied to show how the ‘Max Profit’ model works. By activating and deactivating the incentives placed on the capital expenditure and on the operating costs, changes in the results are highlighted. This allows gaining more insight about how each individual incentive scheme impacts on the model solution. In the following section a summarised description of the mathematical model formulation is first introduced followed by a detailed description of how the profit equation has been obtained and by the detailed list of all model constraints. The nomenclature is also presented to help the reader become familiar with the new terms introduced in the model formulation.

5.2 Regulating private water utilities

Regulation is necessary for privatised natural monopoly firms (Budds and McGranahan, 2003). Natural monopolies occur when a single firm can produce the market quantity at lower production costs than two or more firms (Dennis W. Carlton, 2005). A common explanation for this is the increasing returns to scale, that is, the larger the producer, the lower its average costs. In such a market, competition among several firms is short-lived (firms reduce to one because of mergers or failures) or inefficient: if multiple firms exist, production employs more resources than necessary (Posner, 1969).

In comparison with firms operating in a competitive market, monopolists tend to overprice and under produce, and therefore realise ‘excess’ profits (Budds and McGranahan, 2003). Concern over the pricing of natural monopolies is the reason for regulating private utilities such as telephone services, natural gas, electricity and water. There are several approaches for regulating such monopolies and these typically involve a price cap (Armstrong et al., 1994, Braeutigam, 1989, Isaac, 1991, Beesley and Littlechild, 1989) and/or rate of return (Baumol and Klevorick, 1970) regulation. Under price cap regulation, the regulator sets an initial cap on the price companies can charge customers or on the allowed weighted average price for the firm’s multiple products. The price is then adjusted every year by the Retail Price Index to consider inflation and by a target productivity factor X (Bernstein and Sappington, 2000, Bernstein and Sappington, 1999).

When determining prices regulators usually employ a ‘fair rate of return’ criterion: the difference between the expected revenue and operating expenditure must be sufficient enough to allow the firm to finance its investment plan by earning a ‘fair’ return on it (Averch and Leland, 1962, Leland, 1974). Regulated firms typically have more information than regulators about future demands and the potential for less costly future provision (Armstrong and Sappington, 2006). Under this information asymmetry, the regulator might not be able to perfectly control the activities of the monopoly producer as well as understand when the firm does not operate at minimum cost, with the consequence of higher prices for customers. To lower this distortion incentives regulation can be used to compare company performance. Financial penalties can then be applied for poor performance whilst good performance is rewarded.

Several authors have attempted to study how price cap regulation impact the investments utilities make (Evans and Guthrie, 2012, Teisberg, 1994, Broer and Zwart, 2013, Guthrie, 2006, Nagel and Rammerstorfer, 2009), with some studies applied to sectors such as transport (Yang and Zhang, 2012, Starkie, 2004) and the telecommunication industry (Kridel et al., 1996, Greenstein et al., 1995). However little literature is available on modelling investment behaviours under the price-cap regulation in the privatised water market.

5.3 Water supply planning in England and Wales

In 1989 the water and sewerage sector in England and Wales was privatised. Since then water companies have been private natural monopolies and are regulated to incentivise cost cutting, sustainable development and quality improvements. To limit the companies’ monopoly market power Ofwat, the Water Services Regulation Authority, uses price cap regulation to control prices and rate of return regulation to set ‘fair’ returns on capital (Armstrong et al., 1994, Matthew Bishop et al., 1994, Byatt, 2013, Saal and Parker, 2001).

Price limits are determined every five years in a periodic review process (PR) which considers costs incurred during the 5-year period (Helm and Rajah, 1994). When setting price limits Ofwat allows companies to recover capital and operating costs that they are expected to incur for the next periodic review period given assumptions on future capital expenditure and operating efficiency (Allan, 2006, NERA, 2002). Incentives for costs savings are also implemented to reward (or penalise) companies that out-perform (or under-perform) the estimates assumed by Ofwat on future capital and operating costs (Summerton, 1998, Ofwat, 2010a).

Every five years companies must submit and publish Water resources Management Plans (WRMPs) and Business Plans. WRMPs set out companies' estimates for future supply and demand and their least cost investment plan for the future. In the water resources business plans, the companies publish future expenditure needs, financing requirements and the implications for their average bills. Until 2011 companies have also submitted annual 'June Returns' reports with detailed performance information (e.g. expenditure comparison by purpose, financial and not-financial measures, key outputs, etc.).

5.3.1 The building block approach

Ofwat uses a 'building blocks' approach to determine price limits. An illustration of this approach is set out in Figure 42. Operating costs are recovered from customers through the bills they pay in the year in which they are incurred (opex building block, see Figure 42) while capital expenditures are recovered over the assets' useful life (between 20 to 100 years for civil infrastructure). For this reason, in place of one building block for the capital expenditure, Ofwat considers two capex building *blocks*: one for depreciation on the asset base and one for the return on the Regulatory Capital Value (RCV). The RCV is the total value of the companies' assets invested in the regulated regime (Ofwat, 2013d).

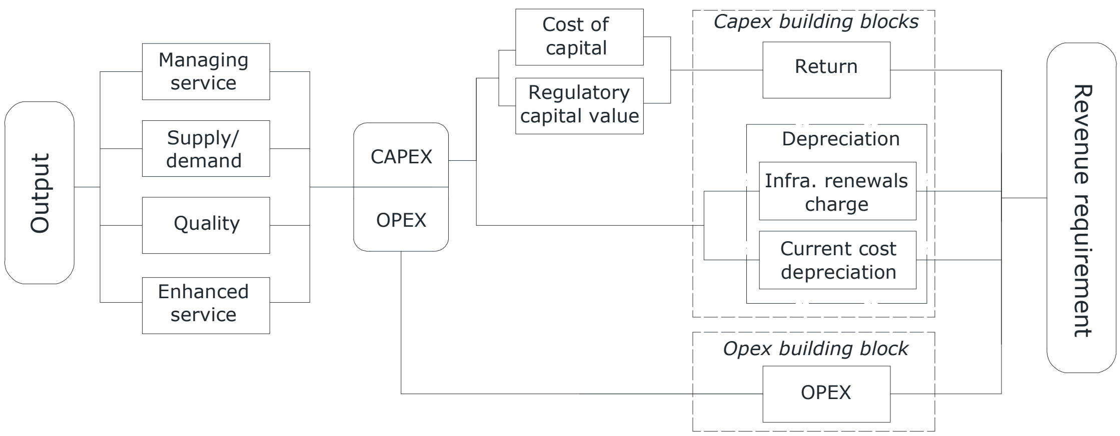

Figure 42: The building block approach, adapted from (Severn Trent Water, 2010).

The maximum price companies can charge customers is calculated as the ratio between the companies' expected revenue requirement and the expected demand. The revenue requirement is the sum of depreciation (DEP), return on the asset base, and operating expenditure. Companies also need to pay corporation tax on their profits.

Once the maximum price is determined, the year to year change in the price limit is fixed (reflecting the assumed level of capital expenditure) for each of the five years until the next periodic review is carried out. The price limit is also adjusted for inflation (through the retail price index, RPI) as it becomes known. Under some circumstances a company can apply for an interim adjustment; this allows price limits to be adjusted between periodic reviews for items whose value exceeds 10% of a company's turnover (Ofwat, 2009b).

Depreciation DEP is composed of two terms: 'infrastructure renewals charge' (IRC) and 'current cost depreciation' (CCD). IRC is the annualised cost of maintaining the system at its current level of operation (Ofwat, 2009b) and is calculated for infrastructure (INFR) assets only. CCD is evaluated for non-infrastructure (N-INFR) assets and is based on the assets' 'Modern Equivalent Asset' value which is the cost to replace an old asset with a new one with the same service capability (Ofwat, 2007). CCD is calculated by dividing the capital expenditure across the N-INFR assets lives (Ofwat, 2002). Classification of INFR and N-INFR assets is reported in (Ofwat, 2013c).

The return on the asset base is obtained by multiplying the Ofwat estimate for the cost of capital, by the company's regulatory capital value. The cost of capital is the rate of return that could be earned elsewhere on assets of equivalent risk (Armstrong et al., 1994) and can be estimated through the Capital Asset Pricing Model or the Dividend Growth Model

At each periodic review, the regulatory capital value of the previous year from the last review is adjusted to consider the movement in Retail Price Index (RPI). Then for each of the 5 years of the periodic review, the expected capital expenditure to enhance and maintain the network is added to the company's regulatory capital value and any expected grant and contribution (G&C) towards the costs on new assets is subtracted along with the depreciation (CCD). Expenditure to maintain and replace infrastructure assets ('IRE' or 'infrastructure renewal expenditure') is not directly accounted for in the RCV, but instead subtracted from the infrastructure renewal charge (IRC). This difference gives an idea of how much more (or less) money has been spent in maintaining the infrastructure asset base than assumed in price limits.

5.3.1.1 Incentives for cost efficiency

Ofwat uses the capital incentive scheme (CIS) to challenge companies to reduce their capital expenditures below the regulatory allowance. Under CIS at the beginning of each periodic review, the company's regulatory capital value RCV is adjusted to include the company's actual capital expenditure of the previous 5 years period and hence a regulatory return is earned on it. Then, if in the previous periodic review, companies out-performed (or under-performed) the Ofwat allowance on the capital expenditure, a reward (or penalty) is added to their revenue requirement for the current review period.

Rewards/penalties are calculated as follows. For each company, Ofwat sets a 'baseline' level for the capital expenditure. The baseline is compared with the company's forecast capital expenditure (as declared in the water resource business plan, WRBP) and is used to calculate the company's expenditure allowance included in price limits. An additional incentive (efficiency incentive) is allowed for further out-performance which declines as the ratio between the 'water resources business plans' forecast and the baseline (referred to as CIS ratio) increases. At each periodic review, CIS rewards/penalties are the difference between the expenditure allowance and the water resources business plans forecast cost at the previous PR, multiplied by the efficiency incentive plus an additional incentive that declines as the CIS ratio increases (OFWAT, 2010b).

Incentives for savings on the operating costs include the operating expenditure incentive allowance. According to these incentive schemes, companies get one hundred percent of any outperformance or underperformance on the operating costs, and can retain the benefits of spending less operating costs than allowed by the regulator, for a total of six years, irrespective of the timing of that spending. At each periodic review, the benefits kept for more than six years are offset against the calculation of the incentive allowance. The incentive allowance benefit is augmented by 50% for the most efficient companies (referred to as frontier company) and by 25% for companies within the 5% of the frontier.

5.3.2 The 'capital bias' issue

When deciding whether to use capital-intensive or opex-intensive solutions, a major factor is whether a company thinks it is more likely to be able to outperform the operating or the capital expenditure (rate of return) assumptions. Over the past years a preference towards expenditure on capital assets over day-to-day operational expenditure (capital bias) has been recorded (Ofwat, 2011, Severn Trent Water, 2010).Causes for 'capital bias' are analysed in detail in (Ofwat, 2011) and mainly include the following: 1. companies earn a rate of return on the capital expenditure, remunerated through the regulatory capital value, while operating costs are recovered from customers in the year it is incurred and earns no such return; 2. to be certain they can meet their security of supply obligations (Water Act, 1989), companies prefer relying on infrastructure they own and control rather than on operating cost-intensive solutions such as imports from neighbouring companies or efficiency programmes whose success depends upon customer's habits and reactions. Since companies are subject to enforcement actions for compliance failures, they may choose capex-based solutions if they think these can guarantee a greater certainty of delivery 3. Companies always retain more information about their businesses than regulators do and might introduce in their water resource business plans unjustified capital expenditures that Ofwat cannot challenge.

5.4 Basic model formulation

5.4.1 Nomenclature

Abbreviations used in the text

PR	periodic review period (this is composed by 5 years)
RCV	company's regulatory capital value: value of the company's assets invested in the regulatory regime
INFR	infrastructure assets: 'underground systems of mains and sewers, impounding and pumped raw, water storage reservoirs, dams, sludge pipelines, sea outfalls, information about infrastructure assets such as zonal investigation records' (Ofwat, 2013c).
N-INFR	Non infrastructure assets: all other assets, typically above ground (Ofwat, 2013c).
DEP	depreciation on the company's asset base. This is the sum of IRC and CCD
IRC	infrastructure renewal charge: annual cost of maintaining the infrastructure system at its current level of operation
CCD	current cost depreciation: non-infrastructure capital expenditure divided by the assets lives
RPI	Retail price index
C&G	company's grant and contributions towards the costs on new assets
IRE	infrastructure renewal expenditure: expenditure to maintain or replace the infrastructure assets

Indices

wc water company

tt different years that belong to the same set t

pr periodic review period

Set

WC set of water companies $WC=\{wc: wc \in WC\}$

T set of time periods. T={t: t is an year and $1 \leq t \leq tmax=26$}

PR set of periodic review periods. PR={pr: pr is a periodic review period and $pr1 \leq pr \leq prmax$}. PR={$pr1, pr2, pr3, pr4, pr5, pr6=prmax$}

T^{fpr} first year of each pr. T^{fpr} ={t: t is an year and t = [1,6,11,16,21,]}

T^{lpr} final years of each pr. T^{lpr} ={t: t is an year and t = [5,10,15,20,25]}

L set of existing and optional transfers and supply options {i, j}

L^{opt} set of optional transfers and supply options {i, j}

$L^{n\text{-}infr}$ set of infrastructure assets

TPR subset of the Cartesian product between T and PR. It defines a mapping between year t of set T and the correspondent periodic review period pr which year t belongs to. TPR= {(t,pr): $t \in T$ and $pr \in PR$ }, that is:

TPR= {$(t1,pr1),\ldots,(t5,pr1),(t6,pr2),\ldots,(t10,pr2),(t11,pr3),\ldots,(t25,pr5)$}

Parameters

io_t regulatory allowance on companies' cost of capital during year t

i_t companies' actual cost of capital during year t

$demand_{wc,t}$ demand for company wc during year t

$demando_{wc,t}$ regulatory estimate of demand for company wc during year t

$ccdo_{wc,t}$	regulatory estimate of current cost depreciation for company *wc* during year *t*
$irco_{wc,t}$	regulatory estimate of infrastructure renewal charge of company *wc* during year *t*
$opexo_{wc,t}$	regulatory estimate of the company's *wc* operating costs during year *t*
$h_{wc,t}$	ratio between $demand_{wc,t}$ and $demandc_{wc,t}$
$fix_{wc,i,j}$	fixed operating costs for L^{opt} assets of company *wc*
$var_{wc,i,j}$	unit variable costs (p/m^3) for of L^{opt} assets of company *wc*
rpi_t	retail price index during year *t*
$gc_{wc,t}$	grants and contribution during year *t* for company *wc*
$sw_{wc,t}$	capital expenditure in the sewage and water sector (e.g. quality enhancement, enhances level service, new outputs/obligations). This does not include costs for maintaining/enhancing the supply-demand balance which are instead optimised by the model
$cap_{wc,i,j}$	capital expenditure of asset *i ,j*
$cw_{wc,t,pr}$	capital expenditure for the water sector (e.g. quality enhancement, enhances level service, new outputs/obligations). This does not include costs for maintaining/enhancing the supply-demand balance
dep_{wc}	current cost depreciation CCD of company *wc* for year 2009
$bas_{wc,t,pr}$	baseline expenditure for company *wc* during year *t*
$pmax_{wc,t}$	maximum price per company *wc* during year *t*
$allowed_{wc,t,pr}$	allowance on capital expenditure for company *wc*, during year *t* and review *pr*
$eff_{wc,t,pr}$	efficiency incentive for company *wc*, during year *t* and review *pr*
$add_{wc,t,pr}$	additional incentive for company *wc*, during year *t* and review *pr*
$gc_{wc,t}$	grants and contributions for company *wc* during year *t*

$ul_{i,j}$ useful life of optional schemes i,j

$f_{wc,t,pr}$ CIS ratio for company wc during year t and review pr

<u>*Variables*</u>

$Q_{wc,i,j,t,scen}$ extent of use of options i,j for company wc, year t and scenario $scen$

$P_{wc,t}$ actual price per company wc during year t

$NPV\pi_{wc,t}$ net present value profit for company wc during year t

$OPEX_{wc,i,j,t}$ weighted operating (fixed plus variable) costs for asset i, j of company wc during year t

$RCV_{wc,t}$ regulatory capital value for company wc during year t

$CCD_{wc,t}$ current cost depreciation for company wc during year t

$IRC_{wc,t}$ infrastructure renewal charge for company wc during year t

$IND_{wc,t}$ Indexation (term used to upgrade the RCV values by inflation)

$CIS_{wc,t,pr}$ rewards/penalties for capex out/under-performances for company wc, during year t and periodic review pr

$IA_{wc,t,pr}$ incentive allowance during year t of periodic review pr, and company wc for out-performances on the operating expenditure

$IAJ_{wc,t,pr}$ equal to $IA_{wc,t,pr}$ when this is positive, and equal to zero otherwise.

$OUT_{wc,t}$ out-performance on operating expenditure during year t and for company wc

$OUTZZ_{wc,t}$ equal to $OUT_{wc,t}$ if this is positive, and zero otherwise (only defined at the final year of each pr).

$MAX_{wc,t}$ max level of opex out-performance for any year prior than t

$ROUT_{wc,t}$ relative out-performance ($OUT_{wc,t}$ - $MAX_{wc,t}$) for company wc, during year t

$ROUTNZ_{wc,t}$ equal to $ROUT_{wc,t}$ if positive, and zero otherwise

$IANEG_{wc,t}$	equal to $IA_{wc,t-1,pr}$ at previous year (*t-1*) if $IA_{wc,t-1,pr}$ is negative, and equal to zero otherwise

Binary Variables

$AL_{i,j,t}$	1 if option *i, j* is activated during year *t*, 0 otherwise
$BS_{wc,i,j}$	1 if option *i, j* is used during any year *t* and demand scenario *scen*, 0 otherwise
$ZZ_{wc,t}$	1 if $OUT_{wc,t}$ is positive during year *t*, 0 otherwise
$X_{wc,t}$	1 if $MAX_{wc,t-1} \geq OUT_{wc,t-1}$ during the previous year *t-1*, 0 otherwise
$Y_{wc,t}$	1 if $ROUT_{wc,t}$ is positive during year *t*, 0 otherwise
$Z_{wc,t}$	1 if variable $IA_{wc,t,pr}$ is negative during year *t*, 0 otherwise

5.4.2 The objective function equation

For each company *wc* (set *WC*) the net present value profit ($NPV\pi_{wc}$) is given by the sum of three terms: 1. the difference between the Ofwat estimated cost of capital (io_t) and the companies' actual (i_t) cost of capital multiplied by RCV; 2. the Ofwat allowance on the operating expenditure (input data, $opexo_{wc,t}$) minus the companies' actual operating costs on selected assets *i*, *j* (variable $OPEX_{wc,i,j,t}$); 3. Penalties (or rewards) for under-performing (or outperforming) the regulatory assumptions on the capital expenditure (CIS scheme, variable $CIS_{wc,t,pr}$) and on the operating costs (opex incentive allowance at year *t* and company *wc*, variable $IAJ_{wc,t,pr}$). $OPEX_{wc,i,j,t}$ contains both fixed and variable operating expenditure. The variable operating expenditure is weighted over multiple demand scenarios (see section 2.1.4 in Chapter 2). CIS rewards/or penalties (variable $CIS_{wc,t,pr}$) are accounted for at the first year *t* of each review *pr* (set T^{fpr}) and multiplied by the baseline expenditure $bas_{wc,t,pr}$ (see CIS scheme).

The profit equation 5.1 also takes into account the revenue correction mechanism, a 'legacy tool' used to deal with differences between the company's actual revenue and the regulatory assumption (see section 5.5.1). Companies' regulatory capital value (RCV) is calculated through an additional constraint: at each year *t*, RCV is equal to the one at the previous year (*t-1*), plus the investments on capital expenditure at year *t*, minus grants and contributions (G&C) and the total depreciation (DEP) during year *t*.

$$
\begin{aligned}
&maximize\ \ NPV\pi_{wc} = \sum_{t=1}^{tmax} \frac{1}{(1+dr)^{t-1}} \times \\
&\Bigg\{ \Bigg[(io_t - i_t) \times RCV_{wc,t} + \Big(opexo_{wc,t} - \sum_{i,j} OPEX_{wc,i,j,t} \Big) \Bigg] \\
&\quad + \sum_{\substack{(t,pr)\in TPR \\ t\in T^{fpr}}} CIS_{wc,t,pr}\Big|_{pr>1} \times \sum_{(tt,pr-1)\in TPR} bas_{wc,tt,pr-1} + \sum_{(t,pr)\in TPR} IAJ_{wc,t,pr}\Big|_{pr>1} \Bigg\} \qquad 5.1 \\
&\forall wc \in WC
\end{aligned}
$$

Profit equation 5.1 shows that under the current regulatory process Ofwat fixes companies' maximum prices such that, for given assumptions about the operating expenditure ($opexo_{wc,t}$), depreciation and cost of capital (ic), the total profit should be zero. A company can therefore achieve a positive profit only if it achieves costs (operating expenditure, depreciation and cost of capital) which are lower than those assumed by the regulator at each price review. A company cannot effectively influence its depreciation which leaves opex and the cost of capital as the only factors a water company can impact. If Ofwat sets a rate of return which is above the actual cost of capital that investors require, then a company can make profit by making capital investments. However if Ofwat sets the rate below the actual cost of capital, then a company will not make profits by investing and hence does not have any incentive to make capital investments. Companies can also make profit by outperforming on the regulatory assumptions on the operating expenditure.

5.4.3 The CIS incentive scheme for capital expenditure

The capital cost incentive scheme's rewards/penalties $CIS_{wc,t,pr}$ are calculated at the first year of each periodic review period (set T^{fpr}) as the difference between the Ofwat allowance on the capital expenditure and companies' actual capital expenditure (optimised by the model) recorded over the five years of the previous periodic review period. Variable $CIS_{wc,t,pr}$ is then multiplied by an efficiency allowance (see section 5.5.3) plus an additional income (see section 5.5.3) determined from companies' CIS ratios. CIS ratio values are obtained from (Ofwat, 2009b). The Variable $CIS_{wc,t,pr}$ is a percentage of the Ofwat established baseline ($bas_{wc,t,pr}$). $CIS_{wc,t,pr}$ is therefore multiplied by $bas_{wc,t,pr}$ related to the previous periodic review period. All costs in this Chapter (including the CIS rewards/penalties) are expressed in M£.

5.4.4 Operating expenditure allowances

The operating cost incentive allowance allows companies to retain one hundred percent of any annual outperformance of under-performance on the operating expenditure (Ofwat, 2010a). This is represented in the objective function equation 5.1 by the difference between the regulatory assumption on opex $opexo_{wc,t}$ and the sum of the operating expenditure $OPEX_{wc,t}$ optimised by the model.

5.4.5 The rolling incentive allowance for operating expenditures

The allowance on operating expenditure is calculated using variable $IAJ_{wc,t,pr}$ which is also included in the objective function equation 5.1. Variable $IAJ_{wc,t,pr}$ is calculated as shown in Figure 43. First the company's outperformance on operating expenditure ($OUT_{wc,t}$) is calculated for every year t of the planning horizon as the difference between the regulatory assumption on the operating costs ($opexo_{wc,t}$) and the company's actual operating expenditure $OPEX_{wc,i,j,t}$. $OPEX_{wc,i,j,t}$ is a continuous positively defined decision variable, defined for selected assets i,j and is estimated considering the most probable scenario (normal year annual average, NYAA) to ensure that variable operating costs (included in the $OPEX_{wc,i,j,t}$ figure) reflect how much schemes are likely to be used over the planning horizon (rather than peak demands maintained all year long). In line with the Ofwat regulatory requirements (Ofwat, 2009b), variable $OUT_{wc,t}$ during the first four years of each periodic review period is forced to be lower than the one at the last (fifth) year of the periodic review.

Once $OUT_{wc,t}$ is known, the relative outperformance ($ROUT_{wc,t}$) at year t is calculated as difference between $OUT_{wc,t}$ and the maximum level of outperformance ($MAX_{wc,t}$) any year before than t. $ROUT_{wc,t}$ is set equal to zero when negative, and this is done by introducing variable $ROUTNZ_{wc,t}$. The Incentive allowance $IA_{wc,t,pr}$ at year t is then calculated as the sum of all relative outperformances $ROUTNZ_{wc,t}$ recorded no more than six years prior to year t. After six years, the relative outperformances are subtracted from the incentive allowance $IA_{wc,t,pr}$ at the first year of each periodic review (see Figure 43).

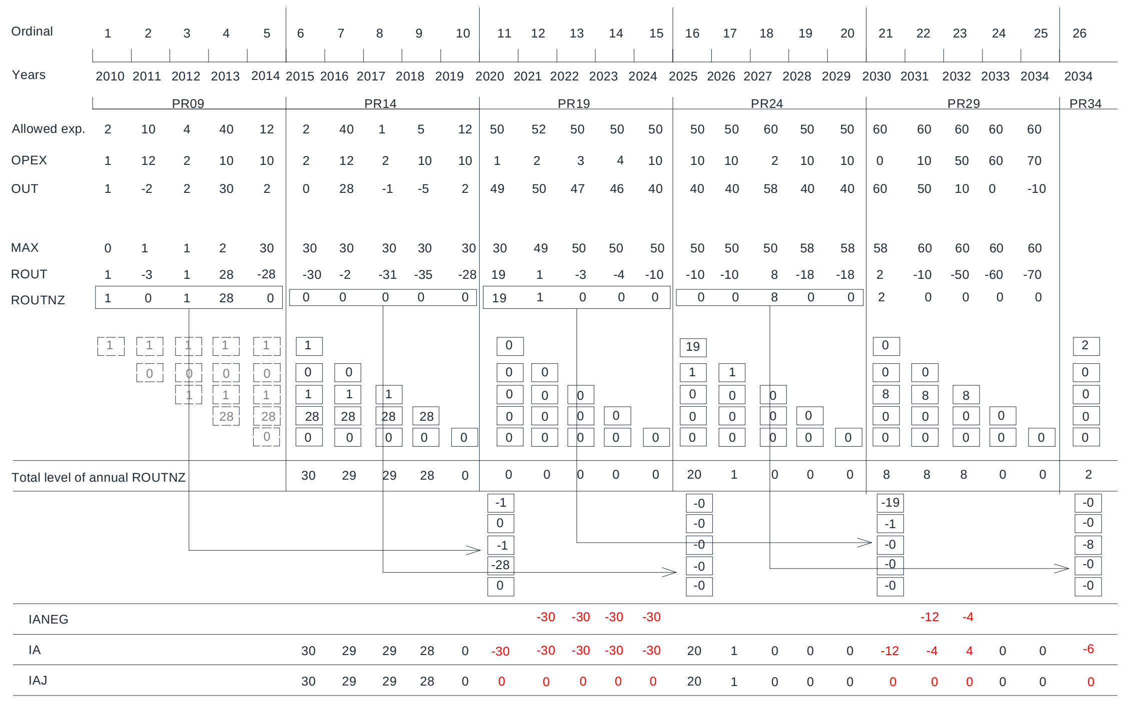

Figure 43: explanatory example on how the rolling incentive allowance for opex out-performances is accounted in between periodic reviews. Numbers in the individual boxes represent the annual relative outperformance (ROUTNZ) on the operating costs for each specific periodic review period. Arrows show subtraction of the relative outperformance values in the boxes after six years have passed from their initial occurrence.

This difference, if negative, is offset against the remaining four years of the periodic review period using variable $IANEG_{wc,t}$, but is not carried forward between reviews.Finally $IA_{wc,t,pr}$ is set to zero, when negative, obtaining variable $IAJ_{wc,t,pr}$ which appear in the objective function equation 5.1 (see also Figure 43). A detailed description of the model formulation is provided below.

5.5 Detailed model formulation

In this section the detailed model formulation is presented. At first, the calculations conducted to obtain the objective function equation 5.1 are shown in section 5.5.1. The regulatory capital value (decision variable $RCV_{wc,t}$) equation is detailed in section 5.5.2, the equation defining CIS rewards/penalties (decision variable $CIS_{wc,t,pr}$) is presented in section 5.5.3, while the rolling incentive allowance equation (decision variable $IAJ_{wc,t,pr}$) is shown in section 5.5.4. Again, in the formulation, variables and set definitions are capital letters and input data are lower case.

5.5.1 The Objective function calculation

Companies' net present value profit is first calculated as in equation 5.2. A loop is also introduced in the model formulation to run the model multiple times, each time for a different water company *wc*.

$$max\ \ NPV\pi_{wc} = \sum_{t=1}^{tmax} \frac{1}{\left(1+dr\right)^{t-1}} \times \begin{Bmatrix} \left(P_{wc,t} \times demand_{wc,t}\right) \\ -\left(CCD_{wc,t} + IRC_{wc,t}\right) \\ -\sum_{i,j} OPEX_{wc,i,j,t} - \left(i_t \times RCV_{wc,t}\right) \end{Bmatrix} \quad \forall\, wc \in WC \tag{5.2}$$

In equation 5.2, *WC* is the set of all companies *wc* , *tmax* the last year of the planning period, $P_{wc,t}$ the price that companies charge to customers during year *t*, $demand_{wc,t}$ is the company's estimated level of future demand while $OPEX_{wc,i,j,t}$ is the sum of fixed and variable operating costs for selected assets *i*, *j* of company *wc* and at year *t*. Finally $CCD_{wc,t}$ and $IRC_{wc,t}$ are respectively the current cost depreciation and the infrastructure renewal charge for company *wc* at time *t*. Terms i_t and $RCV_{wc,t}$ are respectively the company's actual cost of capital and regulatory capital value. The multiplication $i_t \times RCV_{wc,t}$ is the company's return of the cost of capital.

As explained in section 5.3.1 the regulator calculates the maximum consumer water price in year *t* ($pmax_{wc,t}$) as the ratio between the revenue requirement and the regulator estimate of the company's expected demand ($demando_{wc,t}$). The revenue requirement is the sum of the expected return on capital, plus the regulator assumed operating expenditure ($opexo_{wc,t}$) and depreciation (sum of current cost depreciation $ccdo_{wc,t}$ and infrastructure renewal charge $irco_{wc,t}$). The return on the cost of capital is obtained by multiplying the regulatory assumption of the company's RCV value ($RCVo_{wc,t}$) by the regulatory assumption io_t on the cost of capital (allowed rate of return). The regulatory allowed maximum price is given by equation 5.3.

$$pmax_{wc,t} = \frac{io_t \times RCVo_{wc,t} + opexo_{wc,t} + (ccdo_{wc,t} + irco_{wc,t})}{demando_{wc,t}} \quad \forall\, wc \in WC, t \in T \tag{5.3}$$

If companies push prices to the regulatory allowed maximum value $pmax_{wc,t}$, then variable $P_{wc,t}$ in equation 5.2 can be replaced by the maximum price allowed by the regulator in equation 5.3. At each periodic review, under the CIS scheme, companies' actual capex is included in their regulatory capital value and the depreciation charges are adjusted to consider companies past actual expenditure. Therefore, in effect, $RCV_{wc,t}=RCVo_{wc,t}$, $IRC_{wc,t}=irco_{wc,t}$ and $CCD_{wc,t}=ccdo_{wc,t}$. This returns the following equation:

$$maximize\ NPV\pi_{wc} = \sum_{t=1}^{tmax} \frac{1}{(1+dr)^{t-1}} \times \begin{Bmatrix} (io_t \times h_{wc,t} - i_t) \times RCV_{wc,t} \\ +(CCD_{wc,t} + IRC_{wc,t}) \times (h_{wc,t} - 1) \\ +opexo_{wc,t} \times h_{wc,t} - \sum_{i,j} OPEX_{wc,i,j,t} \end{Bmatrix} \quad 5.4$$

$\forall\, wc \in WC$

In the equation above $h_{wc,t}$ is the ratio between the company's estimated annual water demand, $demand_{wc,t}$,and the regulatory estimate for the company's demand $demandc_{wc,t}$. The regulator ensures that $demandc_{wc,t}$ equals $demand_{wc,t}$. If it doesn't, then the company either gets more or less revenue in the next regulatory period to offset the difference. This approach is called the 'revenue correction mechanism'. By assuming that h_t= ($demand_{wc,t}$/ $demandc_{wc,t}$)=1, equation 5.4 becomes:

$$NPV\pi_{wc} = \sum_{t=1}^{tmax} \frac{1}{(1+dr)^{t-1}} \times \begin{Bmatrix} (io_t - i_t) \times RCV_{wc,t} + \\ opexo_{wc,t} - \sum_{i,j} OPEX_{wc,i,j,t} \end{Bmatrix} \quad \forall\, wc \in WC \quad 5.5$$

The company's operating expenditure is expressed by the decision variable $OPEX_{wc,t}$ in equation 5.4. $OPEX_{wc,t}$ is given by the sum of the fixed operating expenditure ($fix_{wc,i,j,t}$) and the variable operating expenditure. Unit variable costs $var_{wc,i,j,t}$ (pound/m^3) are multiplied by extent of annual use variable $Q_{wc,i,j,t,scen}$ and then weighted over the demand scenarios (set *scen*).

$$OPEX_{wc,i,j,t} = \begin{Bmatrix} (fix_{wc,i,j} \times AL_{wc,i,j,t}) \\ + \frac{\sum_{scen} tscen_{scen} \times var_{wc,i,j} \times Q_{wc,i,j,t,scen}}{\sum_{scen} tscen_{scen}} \end{Bmatrix} \quad 5.6$$

$\forall wc \in WC, (i,j) \in L^{opt}, t \in T$

By including the incentives on costs savings the objective function equation 5.5 we obtain equation 5.1.

5.5.2 Company Regulatory Capital Value

Companies regulatory capital value ($RCV_{wc,t}$) is calculated in equation 5.7 for each year *t* and company *wc*.

$$RCV_{wc,t} = \left(RCV_{wc,t-1} + IND_{wc,t} \Big|_{t \in T^{fpr}} \right) - gc_{wc,t}$$
$$+ sw_{wc,t} + cap_{wc,i,j} \times \left(AL_{i,j,t} - AL_{i,j,t-1} \right) \qquad \forall wc \in WC,\ t \in T \qquad 5.7$$
$$- \left(dep_{wc} + \sum_{(i,j) \notin L^{infr}} \frac{cap_{wc,i,j,t}}{ul_{i,j}} \times AL_{i,j,t} \right)$$

In the first year of each periodic review *pr* (set T^{fpr}), $RCV_{wc,t}$ is updated to consider inflation (term $IND_{wc,t}$). Term $gc_{wc,t}$ (equation 5.7) represents the company's grants and contributions towards the costs on new assets, $cap_{wc,i,j}$ is the capital expenditure of schemes *i,j* selected by the optimisation mode to maintain/enhance the supply-demand balance, while $sw_{wc,t}$ is the capital expenditure for the sewage service and other purposes in the water sector (e.g. quality enhancements, customer services, etc.). Term $cap_{wc,i,j}$ is only accounted at the first year of activation of schemes *i,j* when the difference ($AL_{i,j,t}$-$AL_{i,j,t-1}$) is one. Total depreciation is the sum of a fixed term dep_{wc} (depreciation on existing assets) plus a second term for selected assets *i,j* ($cap_{wc,i,j,t}$ is divided by the assets' useful life $ul_{i,j}$).

$IND_{wc,t}$ in equation 5.7 is the indexation term (used to update the RCV values by the inflation). This is calculated as below:

$$IND_{wc,t} = \frac{rpi_{t-1} - rpi_{t-2}}{rpi_{t-2}} \Bigg|_{t \in T^{fpr}} \times RCV_{wc,t-1} \qquad \forall wc \in WC,\ t \in T \qquad 5.8$$

Rpi_t is the retail price index at year *t*. Placing equation 5.8 into equation 5.7 results in:

$$RCV_{wc,t} = \left(RCV_{wc,t-1} \times \frac{rpi_{t-1}}{rpi_{t-2}} \Bigg|_{t \in T^{fpr}} \right)$$
$$+ sw_{wc,t} + cap_{wc,i,j} \times \left(AL_{i,j,t} - AL_{i,j,t-1} \right) \qquad \forall wc \in WC,\ t \in T$$
$$- \left(dep_{wc} + \sum_{(i,j) \notin L^{n-infr}} \frac{cap_{wc,i,j}}{ul_{i,j}} \times AL_{i,j,t} \right) - gc_{wc,t} \qquad 5.9$$

5.5.3 Incentives on capital expenditure (CIS scheme)

At each periodic review *PR*, CIS rewards/penalties (variable $CIS_{wc,t,pr}$) are equal to the difference between the Ofwat allowed capital expenditure and the companies' actual capital expenditure. This difference is then multiplied by an efficiency allowance ($eff_{wc,pr}$) plus an additional income term: $add_{wc,t,pr}$ (equation 5.10).

$$CIS_{wc,t,pr} = \left(\begin{array}{l} \sum_{(tt,pr-1)\in TPR} allowed_{wc,tt,pr-1} - \\ \sum_{(tt,pr-1)\in TPR} \dfrac{\left[\begin{array}{l} cw_{wc,tt,pr} + \\ \sum_{i,j\notin lft} cap_{wc,i,j} \times \left(AL_{i,j,tt} - AL_{i,j,tt-1} \right) \end{array} \right]}{bas_{wc,tt}} \end{array} \right) \times eff_{wc,t,pr} + add_{wc,t,pr} \qquad 5.10$$

$$\forall wc \in WC, (t, pr) \in TPR, t \in T^{fpr}, pr > 1$$

Terms $allowed_{wc,t,pr}$, $add_{wc,t,pr}$ and $eff_{wc,t,pr}$ in equation 5.10 are calculated from companies' CIS ratios ($f_{wc,t,pr}$) respectively in equations 5.11, 5.12and 5.13 (Ofwat, 2009b). Term $cw_{wc,pr}$ is the capital expenditure for all purposes (e.g. quality enhancement, customer service, etc.) excluding those for maintaining the supply-demand balance ($cap_{wc,i,j}$) which are optimised by the model.

$$allowed_{wc,t,pr} = 75 + 0.25 \times f_{wc,t,pr} \qquad 5.11$$

$$\forall wc \in WC, t \in T^{fpr}, pr \in PR, (t, pr) \in TPR$$

$$eff_{wc,t,pr} = \begin{cases} 0.8 - 0.005 \times f_{wc,t,pr} & if \quad f_{wc,t,pr} > 100 \\ 1.5 - 0.0075 \times f_{wc,t,pr} & if \quad f_{wc,t,pr} \le 100 \end{cases} \qquad 5.12$$

$$\forall wc \in WC, t \in T^{fpr}, pr \in PR, (t, pr) \in TPR$$

$$add_{wc,t,pr} = \begin{cases} -5 + 0.175 \times f_{wc,t,pr} - 0.00125 \times f^2_{wc,t,pr} & if \;\; 100 < f_{wc,t,pr} \le 130 \\ -10 + 0.2875 \times f_{wc,t,pr} - 0.001875 \times f^2_{wc,t,pr} & if \quad f_{wc,t,pr} \le 100 \\ -5 + 0.175 f - 0.00125 \times f^2_{wc,t} - (0.05 \times \Delta f^2_{wc,t,pr}) & if \quad f_{wc,t,pr} > 130 \end{cases} \qquad 5.13$$

$$\forall wc \in WC, t \in T^{fpr}, pr \in PR, (t, pr) \in TPR$$

$\Delta f_{wc,t,pr}$ is the extra point of *CIS ratio* behind the 130 upper limit (e.g. if a company has a 150 *CIS ratio* $\Delta f_{wc,t,pr}$ is equal to 20) (OFWAT, 2010b).

5.5.4 Opex rolling Incentive Allowance

The opex rolling mechanism allows companies to retain the benefit ($IAJ_{wc,t,pr}$) of spending less operating costs than allowed by regulators for six years, irrespective of the timing of those savings. Its calculation is explained below.

5.5.4.1 The outperformance on the operating expenditure

Companies' annual outperformance ($OUT_{wc,t}$, equation 5.14) is first evaluated as the difference between the Ofwat allowance ($opexo_{wc,t}$) and the company's actual ($OPEX_{wc,i,j,t}$).

$$OUT_{wc,t} = \left(opexo_{wc,t} - \sum_{i,j} OPEX_{wc,i,j,t} \right) \quad \forall wc \in WC, t \in T, t < tmax \tag{5.14}$$

At each periodic review period pr, the outperformance $OUT_{wc,t}$ cannot be higher than $OUTZZ_{wc,t}$ at the last year of the pr and set out in Equation 5.15 (OFWAT, 2010b).

$$OUT_{wc,t} \leq OUTZZ_{wc,tt} \quad \forall wc \in WC, \left(tt - 5\right) < t < tt \in T^{lpr}, tt < tmax \tag{5.15}$$

In the equations below m is a scalar, while $ZZ_{wc,t}$ is a binary variable equal to one if $OUTZZ_{wc,t} \geq 0$ and equal to zero otherwise. Equations5.16, 5.17, and 5.18 fix variable $OUTZZ_{wc,t}$ equal to zero when $ZZ_{wc,t}$ =0 (and $OUT_{wc,t}$ is negative), and equal to $OUT_{wc,t}$ when $ZZ_{wc,t}$ =1 (and $OUT_{wc,t}$ is positive).

$$ZZ_{wc,t} \times m > OUT_{wc,t} \geq m \times \left(ZZ_{wc,t} - 1 \right)$$
$$\forall wc \in WC, t \in T^{lpr}, t < tmax \tag{5.16}$$

$$OUTZZ_{wc,t} \leq OUT_{wc,t} + m \times \left(1 - ZZ_{wc,t} \right)$$
$$\forall wc \in WC, t \in T^{lpr}, t < tmax \tag{5.17}$$

$$OUTZZ_{wc,t} \leq m \times ZZ_{wc,t} \quad \forall wc \in WC, t \in T^{lpr}, t < tmax \tag{5.18}$$

5.5.4.2 Maximum Outperformance

For any year t the highest level of out-performance achieved in all years before (variable $MAX_{wc,t}$) is calculated in the following way. $MAX_{wc,t}$ is set equal to zero at the first year of the planning horizon $t1$ (equation 5.19) and then equal to $OUT_{wc,t}$ at the second year $t2$ (equation 5.20).

$$MAX_{wc,t} = 0 \quad \forall wc \in WC, t = t1 \tag{5.19}$$

$$MAX_{wc,t} = OUT_{wc,t} \quad \forall wc \in WC, t = t2 \qquad 5.20$$

For each remaining year t of the planning horizon (excluding $tmax$), $MAX_{wc,t}$ is defined by equations 5.21, 5.22 and 5.23 as the maximum value between variables $MAX_{wc,t-1}$ and $OUT_{wc,t-1}$ at year $t-1$.

$$m \times X_{wc,t} > \left(MAX_{wc,t-1} - OUT_{wc,t-1}\right) \geq m \times \left(X_{wc,t} - 1\right) \qquad 5.21$$
$$\forall wc \in WC, t \in T, t2 < t < tmax$$

In the equation above $X_{wc,t}$ is a binary variable, equal to one if, at year $t-1$, $MAX_{wc,t-1} \geq OUT_{wc,t-1}$ and equal to zero otherwise (equation 5.21). Equations 5.21, 5.22 and 5.23 force together the equality $MAX_{wc,t} = MAX_{wc,t-1}$ when $X_{wc,t} = 1$ and $MAX_{wc,t} = OUT_{wc,t-1}$ when $X_{wc,t} = 0$

$$m \times \left(1 - X_{wc,t}\right) \geq \left(MAX_{wc,t} - MAX_{wc,t-1}\right) \geq -m \times \left(1 - X_{wc,t}\right) \qquad 5.22$$
$$\forall wc \in WC, t \in T, t2 < t < tmax$$

$$m \times X_{wc,t} \geq \left(MAX_{wc,t} - OUT_{wc,t-1}\right) \geq -m \times X_{wc,t} \qquad 5.23$$
$$\forall wc \in WC, t \in T, t2 < t < tmax$$

5.5.4.3 The relative Outperformance

For each company wc and year t, the relative outperformance (variable $ROUT_{wc,t}$) is the difference between $OUT_{wc,t}$ and $MAX_{wc,t}$ at year t (equation5.24). $Y_{wc,t}$ is a binary variable equal to one if $ROUT_{wc,t} \geq 0$, and equal to zero otherwise (equation 5.25).

$$ROUT_{wc,t} = \left(OUT_{wc,t} - MAX_{wc,t}\right) \quad \forall wc \in WC, t \in T, t < tmax \qquad 5.24$$

$$\left(Y_{wc,t} \times m\right) > ROUT_{wc,t} \geq \left(Y_{wc,t} - 1\right) \times m \quad \forall wc \in WC, t \in T, t < tmax \qquad 5.25$$

$ROUTNZ_{wc,t,pr}$ is a positive continuous variable equal to zero if $ROUT_{wc,t} < 0$ and equal to $ROUT_{wc,t}$ if $ROUT_{wc,t} \geq 0$ (equations 5.26 and 5.27).

$$ROUT_{wc,t} \leq ROUTNZ_{wc,t,pr}\Big|_{(t,pr) \in TPR} \leq ROUT_{wc,t} + m \times \left(1 - Y_{wc,t}\right) \qquad 5.26$$
$$\forall wc \in WC, t \in T, t < tmax, pr \in PR$$

$$ROUTNZ_{wc,t,pr}\Big|_{(t,pr)\in TPR} \le m_{wc} \times Y_{wc,t} \quad \forall wc \in WC, t \in T, t < tmax, pr \in PR \tag{5.27}$$

5.5.4.4 Incentive Allowance

The incentive allowance $IA_{wc,t,pr}$ at year t is first calculated as the sum of all the relative annual outperformances ($ROUTNZ_{wc,t,pr}$) recorded no more than six years before t. $ROUTNZ_{wc,t,pr}$ kept for more than 6 years are subtracted from variable $IA_{wc,t,pr}$ at the first year of each periodic review pr (*set* T^{fpr}). This difference is then offset against the value of $IA_{wc,t,pr}$ over the next four years of the periodic period pr by using variable $IANEG_{wc,t,pr.}$ (equation 5.28).

$$IA_{wc,t,pr}\Big|_{(tt,pr)\in TPR} = \left[\begin{array}{l} \sum\limits_{\substack{(tt,pr)\in TPR \\ tt+5\ge t}} ROUTNZ_{wc,tt,pr-1} - \\ \sum\limits_{\substack{(tt,pr)\in TPR \\ pr>2}} ROUTNZ_{wc,tt,pr-2}\Big|_{tt\in T^{fpr}} + IANEG_{wc,tt,pr}\Big|_{pr>2} \end{array}\right] \tag{5.28}$$
$$\forall wc \in WC, t \in T, pr > 1$$

$IANEG_{wc,t,pr}$ is defined by equations 5.30, 5.31, and 5.32. For each year $t>t5$ (i.e. after the first periodic review period, $pr>1$), binary variable $Z_{wc,t}=1$ (equation 5.29) if $IA_{wc,t,pr}$ is strictly negative, and $Z_{wc,t}=0$ otherwise. $IANEG_{wc,t,pr}$ is forced to zero at years T^{fpr} (equation 5.29).

$$\left(1 - Z_{wc,t}\right) \times m > IA_{wc,t,pr}\Big|_{(t,pr)\in TPR} \ge -m \times Z_{wc,t} \quad \forall wc \in WC, t \in T, pr \in PR, pr > 1 \tag{5.29}$$

$$IANEG_{wc,t,pr} = 0 \quad \forall wc \in WC, t \in T \wedge t \in T^{fpr}, pr > 2 \tag{5.30}$$

Variable $IANEG_{wc,t,pr}=0$ at any year t and for any periodic review $pr>1$, if $IA_{wc,t,pr}$ at the previous year (t-1) is positive (and therefore $Z_{wc,t}=0$). Otherwise, $IANEG_{wc,t,pr}=IA_{wc,t,pr}$ at year t-1 if $IA_{wc,t,pr}$ is negative (and therefore $Z_{wc,t}=1$), see equations 5.31 and 5.32. $IANEG_{wc,t,pr}$ values are not carried forward between reviews.

$$\left[IA_{wc,t-1,pr} - m\times\left(1-Z_{wc,t-1}\right)\right] \le IANEG_{wc,t,pr} \le \left[IA_{wc,t-1,pr} + m\times\left(1-Z_{wc,t-1}\right)\right] \quad 5.31$$
$$\forall wc \in WC, t \in T \wedge t \notin T^{fpr}, pr > 2, (t, pr) \in TPR$$

$$-\left(m \times Z_{wc,t-1}\right) \le IANEG_{wc,t,pr} \le \left(m \times Z_{wc,t-1}\right) \quad 5.32$$
$$\forall wc \in WC, t \in T \wedge t \notin T^{fpr}, pr > 2, (t, pr) \in TPR$$

Variable $IAJ_{wc,t,pr}$ (the incentive allowance term included in the objective function equation 5.1) is set equal to $IA_{wc,t,pr}$ if $Z_{wc,t}$=0, and equal to zero when $Z_{wc,t}$=1 (i.e. when $IA_{wc,t,pr}$ is negative), see equation 5.33 and 5.34.

$$IAJ_{wc,t,pr}\Big|_{(t,pr)\in TPR} \le IA_{wc,t,pr}\Big|_{(t,pr)\in TPR} + \left(m\times Z_{wc,t}\right) \quad \forall wc \in WC, t \in T, pr > 1 \quad 5.33$$

$$IAJ_{wc,t,pr}\Big|_{(t,pr)\in TPR} \le m\times\left(1-Z_{wc,t}\right) \quad \forall wc \in WC, t \in T, pr > 1 \quad 5.34$$

Finally $IAJ_{wc,t,pr}$ is incremented (see term $mult_{wc}$ in equation 5.35) by 50% for companies at the efficiency frontier (Ofwat, 2009b) and the 25% for companies within 5% of the frontier. The enhanced benefit is then spread over the five years of the price review, *pr*. Equation 5.33 therefore becomes:

$$IAJ_{wc,t,pr}\Big|_{(t,pr)\in TPR} \le \left[\begin{array}{l} IA_{wc,t,pr}\Big|_{(t,pr)\in TPR} \\ +\left(mul_{wc} \times \dfrac{1}{5} \times \displaystyle\sum_{(tt,pr-1)\in TPR} ROUTNZ_{wc,tt,pr-1}\right)\end{array}\right] + \left(m\times Z_{wc,t}\right) \quad 5.35$$
$$\forall wc \in WC, t \in T, pr > 1$$

5.5.5 Further constraints

As most *i,j* schemes have a lower bound capacity equal to zero, the ‘Max profit’ model might activate schemes ($AL_{i,j,t}$=1) at zero ‘flow’($Q_{wc,i,j,t,scen}$=0) to maximise companies’ profit. To avoid this, a new binary variable $BS_{wc,i,j}$ is introduced, equal to one if option *i,j* is used (that is if $Q_{wc,i,j,scen}$>0 in any year *t* and scenario *scen*) and equal to zero otherwise (equation 5.36).

$$\sum_t \sum_{scen} Q_{wc,i,j,t,scen} \ge BS_{wc,i,j} \ge \frac{\sum_t \sum_{scen} Q_{wc,i,j,t,scen}}{m}$$
$$\forall wc \in WC, (i, j) \in L^{opt} \quad 5.36$$

Equation 5.37 forces $AL_{i,j,t}$ to zero when $BS_{wc,i,j}$ is zero (i.e. when option *i*, *j* is never used).

$$AL_{wc,i,j,t}\Big|_{t=tmax} = BS_{wc,i,j} \quad \forall wc \in WC, (i, j) \in L^{opt}, t \in T \qquad 5.37$$

5.5.6 List of model constraints

The 'Max Profit' model here presented has equation 5.1 as objective function equation, and equations 5.9 to 5.37 as model constraints. Other model constraints are in common with the 'Min Cost' model presented in Chapter 2 and include the mass balances (equation 2.12), capacity constraints of all companies' proposed schemes *i*,*j* (equations 2.6 and 2.7), constraints in section 2.1.5 and 2.1.5 and the demand reduction approach for model infeasibilities (section 2.1.7.2). Variable costs of selected schemes are calculated as in Chapter 2 (equation 2.15).

5.6 Model application

The profit maximisation model introduced in this Chapter is referenced as 'Max Profit', and the EBSD model introduced in Chapter 2 as 'Min Cost'. The 'Min Cost' and 'Max Profit' models are solved for a company 'WC1' in the South East of England. This company is a subset from the WRSE network shown in Figure 23 of Chapter 3.

Company's past expenditures (period 2003-2009) are extrapolated from the June Return reports. Such values are then interpolated to make an estimate of the company's future expenditures over the 2010-2035 planning horizon. The company' RCV values at the first year of the planning horizon are taken from the Ofwat website (Ofwat, 2012). The CIS ratios for year 2010 is from Ofwat (2010b). CIS ratios are hypothesised to be constant over the planning horizon. The future values for the retail price index are also interpolated from historical data available on line. The regulatory allowance on the company's operating costs is equal to the operating costs in the least-cost solution (obtained by running model 'Min Cost'), while the allowance on the capital expenditure is set accordingly according to the CIS scheme. The company's CIS ratio found in Ofwat (2010b). For simplicity, the CIS ratio is hypothesised to be constant over the planning horizon.

The planning period is composed of 26 years and is divided into five slots of five years each (price reviews, 'PR'). The last PR only includes year 2035, due to data availability. Three demand scenarios (DYAA, DYCP and NYAA) are considered (see Chapter 1 for their definition). The regulatory assumption on the cost of capital io_t and the company's actual cost of capital i_t are model input data. The difference (io_t-i_t) is initially considered to be constant over the planning horizon (i.e. Dic=io-i), and sensitivity analysis is used to check the model response to different values of Dic. The model formulation is then expanded to examine the cases where a 'capital bias' occurs. If a 'capital bias' is found in a specific periodic review period, at the next 5 year review period the gap (io_t-i_t) is set to a constant negative value -Dic (i.e. the allowed cost of capital is fixed below the company's actual cost of capital). Sensitivity analysis is then performed to see if the 'capital bias' could be eliminated by decreasing values of –Dic.

Ofwat differentiates costs between expenditures for delivering and maintaining the existing level of service (referred to as 'base service', see Figure 44) and expenditure to meet new needs or delivering improvements to service (known as 'enhancement', see Figure 44). The 'base expenditure' is then divided further into operating and capital maintenance expenditure; the latter is composed of infrastructure renewal expenditure IRE and maintenance non-infrastructure. Enhancement investment is instead categorised as 'quality', 'supply-demand balance' or 'enhanced service level'. The Ofwat regulatory accounting guideline (Ofwat, 2003, Ofwat, 2013b) contains a detailed classification of the water companies' expenditure categories.

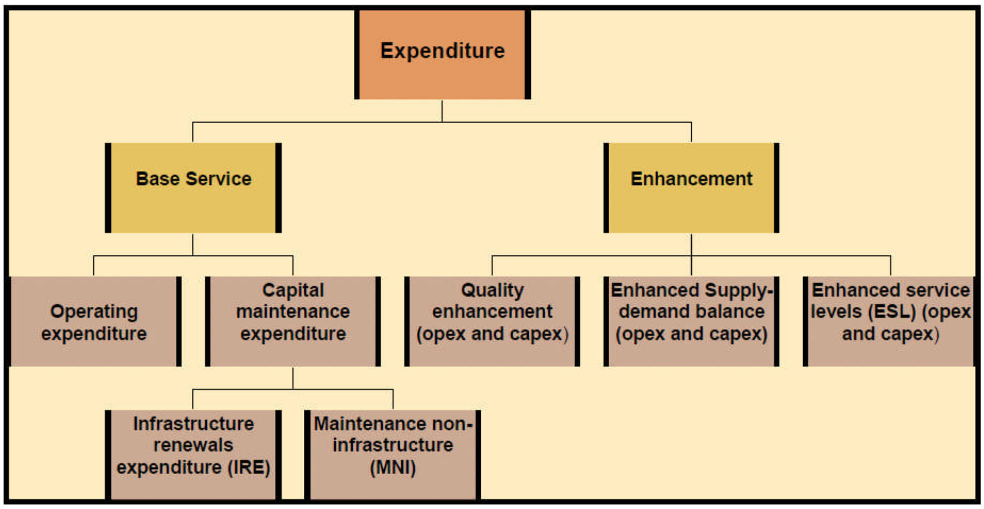

Figure 44:Ofwat expenditure categories, adopted from (Ofwat, 2008).

The model does not optimise all of the expenditure categories related to the water service, but only the investment decisions which fall within the category 'enhanced supply-demand balance' (see Figure 44). This is the 'expenditure to provide water services for new customers and/or accommodate the increased use of water by existing customers at the current level of service'(Ofwat, 2003). This includes operating expenditure and the infrastructure of non-infrastructure expenditure (Ofwat, 2009a).

Both operating cost (fixed and variable) and the capital expenditure are considered for supply-side schemes and demand management measures. Negative operating costs (savings) are generated by leakage options. Such schemes reduce the amount of water to treat and transport in the network, resulting in savings in energy and chemicals. With regards to imports from external areas (collectively referred to by set TR), the operating costs are assigned to the importing company only, whilst capital expenditure is shared between the importing and the supplying company (Ofwat, 2013a). The 'Max Profit' model is applied at a company level, which means that when import schemes are activated (based on their costs and maximum capacity), the model does not take into account the supply-demand balance condition in the exporting company.

All schemes in the analysed network are divided into infrastructure (or underground) and non-infrastructure (or surface) assets. This distinction was made by following the Ofwat regulatory accounting guidelines (Ofwat, 2003, Ofwat, 2013b) that define infrastructure assets and the Ofwat's PR09 Financial Modelling Rule book (Ofwat, 2009a) which show how all the various operating and capital cost items are treated in the final determination of price limits.

In the model, infrastructure assets include: 'underground systems of mains and sewers, impounding and raw water storage reservoirs, dams, sludge pipelines, see outfalls and information about infrastructure assets (e.g. zonal investigation records')'. Reservoir schemes, transfers and active leakage control schemes, which also include zonal investigations, were therefore considered as infrastructure assets. All remaining schemes are classified as non-infrastructure.

Non-infrastructure assets are depreciated. The depreciation term is subtracted from the company's Regulatory Capital Value. Ofwat calculates companies' current cost depreciation based on the 'Modern Equivalent Asset' (MEA) value. The 'Modern Equivalent Asset' value of an asset is what it would cost to 'replace an old asset with a technically up to date one with the same service capability' (Ofwat, 2002). When the asset is new, its capital cost and the 'Modern Equivalent Asset' value are the same. As the asset gets older, there is the need to update its original capital cost figure to obtain its 'Modern Equivalent Asset' value. This is done by allowing for inflation in capital-items costs and by taking into account technological progress (which may have made an equivalent asset a lot cheaper to buy now than it was for example 20 years ago). Since the model considers the activation of new schemes over a planning horizon, the schemes' capital expenditures were considered equivalent to the 'Modern Equivalent Asset' value. Current cost depreciation is therefore calculated by spreading capital costs over the assets expected useful life (Ofwat, 2002). This depreciated amount is then summed up to a fixed term (depreciation value in year 2009, from the companies' June returns) in order to consider the depreciation on the existing assets. The assets' useful life is set equal to 25 years for desalination schemes, 60 years for all remaining assets (Halcrow, 2005) and 30 for metering schemes based on information from (EA, 2005a).

Infrastructure assets are not depreciated; Ofwat uses for these asset type an average of the projected renewal spend (infrastructure renewal expenditure or IRE). The infrastructure renewal expenditure is not directly added to the companies' Regulatory Capital Value but is subtracted from the infrastructure renewal charge IRC (i.e. only the variations in the accumulated pre-payment/accrual of IRC-IRE are considered). Infrastructure renewal expenditure and network-enhancement are different categories of capex (see Figure 44) and the model only optimises the latter expenditure type. Given the definition of infrastructure renewal charges based on past and future renewal expenditures (Ofwat, 2009a), the difference between the renewal spend additions and infrastructure renewal charge subtractions was considered equal to zero in the model, and therefore leave the Regulatory Capital Value at the same level. Only extra or enhanced infrastructure or non-infrastructure assets increase the company's Regulatory Capital Value.

The model considers that, under the PR09 approach, first time spending on infrastructure assets increases the Regulatory Capital Value and so a return is earned on this increase. This is done following the Ofwat's PR09 'financial model rule book' (Ofwat, 2009a) which specifies that all of the capital expenditure to enhance the network (which is also infrastructure, as specified before) is added to the Regulatory Capital Value: '*Capital expenditure to enhance and maintain the network is added to the RCV. Any capital grants or contributions towards the cost of the new assets are deducted. Current cost depreciation (based on the MEA value of the assets) is deducted from the RCV each year'*.

Of course, the exact increase in the Regulatory Capital Value and the exact amount of return depends on the full calculation of the PR09 price setting mechanism. This includes the Ofwat's final allowance for the capital expenditure relative to the company's Business Plan submission, the outturn (the company's eventual capex spend relative to the allowance, with all the Ofwat adjustments for shortfalling/logging/inflation) plus the menu-selected proportions (e.g. CIS scheme, incentive allowances on the operating costs).

5.7 Model statistics and input costs data

5.7.1 Statistics

Both the ‘Max Profit’ and ‘Min Cost’ models are implemented in GAMS (Brooke A et al., 2010) and solved using the CPLEX MILP solver. The model was in a Windows XP environment, using a DELL 2.6 GHz machine with 16 GB RAM. Figure 39 provides statistics for model ‘Max Profit’. Model ‘Max Profit’ converges to a 2% gap in about 40 minutes time.

	Model statistics	
	‘Min Cost’	‘Max Profit’
Total number of variables	13,212	13,714
Binary variables	3,617	3,769

Table 39: Model statistics for the cost minimising model (‘Min Cost’) and the utility profit maximisation model (‘Max Profit’).

5.7.2 Capital and operating costs for the analysed network

Figure 45 in panel ‘a’ shows the ratio (in percentage) between the capital cost of proposed future schemes (grouped by type) and the total capital expenditure from all the optional schemes. Schemes types are the same as in Chapter 2 (see section 2.2.1). Likewise, panel ‘b’ shows the same ratio but for the operating expenditure. Costs data are from the company water resources management plan submitted during year 2009 and are extrapolated from aggregated information as explained in Chapter 3 (section 3.4). Since the model optimises decisions (what to build and at what capacity) based on schemes’ capital expenditures and operating costs, and since the 2010-14 regulatory process promotes separate incentives for costs savings on the capital and operating costs, it is important to understand which schemes are capital cost-based or operating cost-based (as shown in Figure 45). The graph in Figure 45 does not determine in absolute terms if a scheme type is capital cost or operating cost based, since the cost data used to generate this graph are approximated. The aim of graph Figure 45 is to show the cost data for company WC1 and which specific option type, for this case study, is capital cost intensive or operating cost intensive. For example, from Figure 45 it is clear that reservoir (RES), aquifer storage and recharge (ASR), metering (MET) and groundwater (GW) schemes are the most capital cost intensive schemes while imports (TR) are the most operating cost intensive schemes for network WC1.

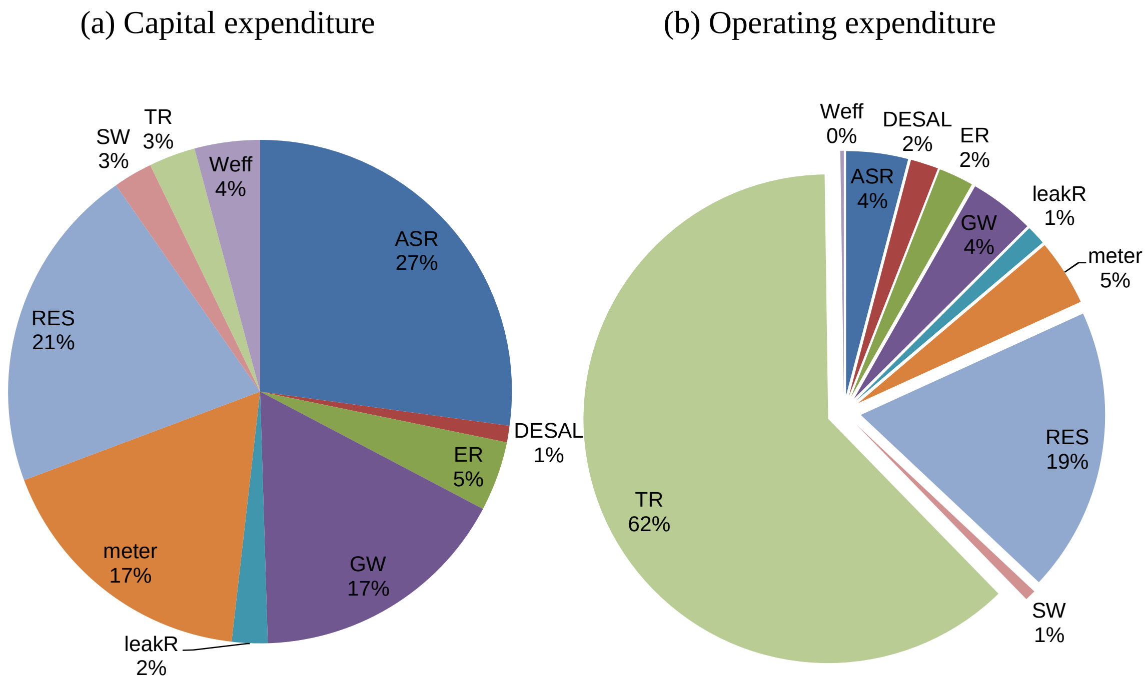

Figure 45: Ratio (in percentage) of each asset type cost (capital expenditure in panel 'a' and fixed plus variable operating costs in panel 'b') and the total capital (panel 'a') or operating (panel 'b') costs of all assets.

5.8 Model results

Solving the 'Min Cost' and 'Max Profit' models provides the year of activation for new options and the extent of annual use in Ml/d of existing and new schemes under the dry year annual average, dry year critical period (DYCP) and normal year annual average demand scenarios.

Table 40 and Table 41 show the total costs of selected schemes grouped by asset type and their optimal extent of use in Ml/d under the DYCP scenario, respectively. Costs in Table 40 are split into capital expenditure, fixed operating expenditure and variable costs. Variable operating costs are weighted over the demand scenarios (see section 2.1.4 in Chapter 2).

	Costs [M£]					
	'Min Cost'			'Max Profit'		
	Capital	Fixed operating	Weighted Variable operating	Capital	Fixed operating	Weighted Variable operating
RES	/	/	/	909	-16	0.16
TR	142	56	90	88	28	5
ASR	93	12	14	108	14	13
ER	27	2	1.28	27	2	1
GW	23	8	0.32	24	8	0.29
DESAL	13	27	6	24	15	3
MET	297	18	/	349	4	/
SW	4	0.36	0.52	4	0.36	1
LEAK	25	-28	/	25	-28	/
WEFF	40	-2	/	40	-2	/
TOTAL	***664***	***92***	***113***	***1597***	***23.9***	***23.7***

Table 40: Discounted costs in M£ for activated optional schemes aggregated by option type under the 'Min Cost' and 'Max Profit' runs. All data refers to company WC1 only. Columns may not add up due to rounding.

	Optimal extent of use [Ml/d]	
	'Min Cost'	'Max Profit'
RES	/	2799
TR	2716	328
ASR	547	511
ER	113	113
GW	271	240
DESAL	882	529
MET	1975	1975
SW	72	72
LEAK	1320	1320
WEFF	185	185
TOTAL	***8080***	***8073***

Table 41: Total extent of use for existing and optional nodes aggregated by option type, under the three demand scenarios, for the 'Min Cost' and 'Max Profit' runs. All data refers to company WC1 only. Columns may not add up due to rounding.

By comparing the least-cost solution (model 'Min Cost') with the solution provided by the utility profit maximising model ('Max profit'), the following differences are noticed. The extent of use of import schemes from external areas (TR) decreases from 2716 Ml/d in 'Min Cost' to 328 Ml/d in 'Max Profit' (see Table 41), over the planning period. Reservoir schemes, not activated in 'Min Cost', are used at a total capacity of 2799 Ml/d in 'Max Profit' (see Table 41).

The capital expenditure increases from M£ 664 in 'Min Cost' to M£ 1597 in 'Max Profit' (see Table 40) mainly due to the activation reservoir options. Fixed operating costs decrease from M£ 92 in 'Min Cost' to M£ 23.9 in 'Max Profit' due to: 1.

activation of less import schemes TR (this reduces the operating costs from M£ 56 in 'Min Cost' to M£ 28 in 'Max Profit'); 2. environmental benefits (negative operating costs, M£ -16) related to reservoir schemes and 3. activation of a 'change of occupancy' metering scheme in 'Max Profit' in place of a 'targeted compulsory' metering (TCM) in 'Min Cost'. The 'change of occupancy' metering scheme has lower operating costs (M£ 17) than the TCM scheme (M£ 1). Weighted variable operating costs decrease from M£ 113 in 'Min Cost' to M£ 23.7 in 'Max Profit' (see Table 40) mainly due to a lower utilisation of imports TR from external areas.

Table 42 shows, for each periodic review period, the company's return on the asset base ($\sum \Delta ic_t RCV_t$), the outperformance on the operating expenditure (Δopex), CIS rewards/penalties and the rolling incentive allowance IAJ for outperformances on the operating costs. All data in Table 42 are in M£. The sum $\sum \Delta ic_t RCV_t$+Δopex+CIS+IAJ gives the company's profit. Term $\Delta ic_t=(io_t-i_t)$ is the difference between the regulatory estimate of the cost of capital (io_t) and the company's actual costs of capital (i_t). $\Delta ic_t=(io_t-i_t)$ is constant ($\Delta ic_t=\Delta ic$) over the planning period and equal to 0.001.

	$\sum \Delta ic_t RCV_t$	Δopex	IAJ	CIS
PR09 (2010-2014)	36	4	/	/
PR14 (2015-2019)	29.5	16	7	66
PR19 (2020-2024)	23	42	15	-36
PR24 (2025-2029)	16	45	9	99
PR29 (2030-2034)	12	43	0.5	86
PR34 (2035)	2	9.5	/	71
TOTAL	***119***	***159.5***	***31.5***	***286***

Table 42: Return on the asset base ($\sum \Delta ic_t RCV_t$), outperformance on the operating expenditure (Δopex), rolling Incentive Allowance (IAJ) and CIS scheme (CIS) for each periodic review period, under model 'Max Profit'.

Since under the CIS scheme both rewards and penalties are allowed (term CIS in Table 42 can be positive or negative), a company may opt to maximise the size of its regulatory capital value (by increasing term $\sum \Delta ic_t RCV_t$) through a combination of rewards/penalties that balance out over time. In Table 42, even with a penalty of M£ -36, the sum of the undiscounted CIS incentives is positive and equal to M£ 286.

Table 43 shows the undiscounted capital expenditure under the 'Min Cost' and 'Max Profit' models runs, for each periodic review period. A capital cost expenditure of M£ 1371 appears in PR14 under the 'Max profit' model due to the activation of a reservoir scheme. This creates an undiscounted CIS penalty M£ 36 at the subsequent periodic review period PR19 (see Table 42).

	PR09	PR14	PR19	PR24	PR29	PR34
‘Min Cost’	505	204	35	20	84	10
‘Max Profit’	486	1371	35	37	105	181

Table 43: Undiscounted capital expenditure in M£ under the least-cost model ‘Min Cost’ and the utility profit maximising ‘Max Profit’ model, under each periodic review period.

Table 44 shows, for each periodic review period, the operating expenditure (fixed plus variable operating costs) under the ‘Min Cost’ and ‘Max Profit’.

	PR09	PR14	PR19	PR24	PR29	PR34
‘Min Cost’	0.7	24	86	128	160	49
‘Max Profit’	-4	2	15	33	48	20

Table 44: Undiscounted operating expenditure in M£ under the ‘Max profit’ and the ‘Min Cost’ model, for each periodic review period.

The operating cost profile in ‘Max Profit’ is lower than the one in ‘Min Cost’. Negative operating cost values in ‘Max Profit’, at the first periodic review period PR09, are mainly due to savings associated to leakage reduction schemes and to a reservoir option activated under the ‘Max Profit’ run only.

5.8.1 Sensitivity analysis on the model results

Results in the previous section reveal that a ‘capital bias’ may occur for company WC1. This is because the ‘Max Profit’ model replaces some of operating cost-based schemes identified in the least-cost plan (see transfers TR, in model ‘Min Cost’) with capital cost-intensive solutions (such as reservoirs).

In this section sensitivity analysis is applied to obtain a higher level of understanding about model ‘Max Profit’. ‘Max Profit’ is run without allowing the company to retain any outperformance on the operating cost, without any of the incentives for costs savings (CIS rewards/penalties, rolling incentive allowance) and for different values of the outperformance on the cost of capital Δic.

Table 45 shows results, over the whole planning horizon, from all model runs which includes the company’s profit (‘Profit’), total costs (‘Total Cost’), costs split into operating (‘Opex’) and capital (‘Capex’) expenditure, CIS incentive rewards/penalties (‘CIS’) and rolling incentive allowance for the operating costs (‘IAJ’). The operating costs (‘opex’ in Table 45) include both the fixed and variable operating expenditures. The return on the company’s regulatory capital value is also shown (see column $\Delta ic \sum_t RCV_t$ in Table 45). For the model runs in Table 45, the outperformance on the cost of capital Δic is constant over the planning horizon and is set equal to 0.001. Column ‘Δopex’ in Table 45 shows the difference between the regulatory allowance on the operating expenditure and the company's actual operating cost (optimised by the model).

	Profit	Cost	Opex	Capex	CIS	IAJ	Δopex	$\Delta ic\sum_t RCV_t$
'Min Cost'	/	870	205	664	/	/	/	/
'Max Cost'	/	10615	8116	2499	/	/	/	/
'Max Profit'	596	1645	48	1597	286	31.5	159.5	119
'Profit_noIAJ'	564.5	1645	48	1597	286	/	159.5	119
'Profit_noINC'	275	1852	53	1799	/	/	154.5	121

Table 45: The utility maximising profit model ('Max profit') is run without allowing the company to retain any outperformance on the operating costs (model 'Profit_noIAJ'),without any of the incentives on capital and operating costs ('Profit_noINC'). In 'Min cost' the cost of future capacity expansions are minimised, while in 'Max Cost' costs are maximised. All costs are discounted to the base year 2010.

When an asset is selected under the utility profit maximising model 'Max profit', the company's regulatory capital value is increased by the asset's capital expenditure and reduced annually by the depreciation for non-infrastructure assets only. In order to demonstrate that the 'Max profit' model is not simply maximising the company's capital expenditure, an additional model ('Max Cost') is run. This model is equivalent to 'Min Cost' with the difference that the net present value costs are maximised. Capital costs in 'Max Profit' (M£ 1597 in Table 45) are lower than in 'Max Cost' (M£ 2499 in Table 45).

If the 'Max Profit' model is run without including the rolling incentive allowance on the operating expenditure (model 'Profit_noIAJ'), than the solution (schedule of schemes) remains unchanged. The company's profit decreases from M£ 596 in 'Max profit' to M£ 564.5 in 'Profit_noIAJ', which is exactly the amount of the incentive allowance IAJ (M£ 31.5 in 'Max Profit' in Table 45) not included in model 'Profit_noIAJ'. This means that the rolling incentive allowance scheme IAJ does not contribute to reducing the company's operating expenditure.

If the utility profit maximising model ('Max Profit') is run without including the IAJ and CIS incentive schemes (model 'Profit_noINC'), the profit equation becomes $\Delta ic\sum_t RCV_t + \Delta opex$. Under the 'Profit_noINC' run, capital costs increase from M£ 1597 (in 'Max Profit') to M£ 1799 (see Table 45). Therefore, the CIS scheme contributes in decreasing capital costs.

In addition to the considerations above, the extent to which a company can out-perform the cost of capital (Δic) can also contribute towards biased solutions. This is shown by running model 'Profit_noINC' for different values of Δic (see Table 46). Table 46 shows that the capital expenditure increases for higher values of Δic. All terms in Table 46 are in M£.

	‘Profit_noINC’					
	Profit	Cost	Capex	Opex	Δopex	$\Delta ic \sum_t RCV_t$
Δic=0	176	1617	1588	29.5	175	/
Δic=0.005	788	2160	2111	49	156	632
Δic=0.01	1421	2230	2176	54	151	1270

Table 46: Changing the values of the outperformance on the cost of capital, for model ‘Profit_noINC’. The data are in M£ and are discounted to year 2010.

Since companies accrue any out- or under- performance on the operating expenditure (term Δopex), they may have the incentive to lower their operating expenditure below the value in the least-cost solution: the operating costs in the ‘Min Cost’ run is equal to M£ 205, while opex in the ‘Max Profit’ run decreases to M£ 48 (see Table 45). This can contribute to a ‘capital bias’ in the sense that a company may opt to replace opex-based solutions by capital-based ones. Even when the outperformance on the cost of capital is zero (see Δic=0 in in Table 46) and no return can be earned on the capital expenditure ($\Delta ic \sum_t RCV_t = 0$), capital costs are higher in the ‘Max profit’ (M£ 1597 in Table 46) solution than in the ‘least-cost’ solution (M£ 664 for ‘Min Cost’ in Table 45).

5.8.1.1 Changing the gap between the allowed and the actual cost of capital

In this section, the ‘Max Profit’ model formulation was extended to examine the case in which the gap, *Δic*, between the allowed and the actual costs of capital is set equal to a negative value when there is a ‘capital bias’ occurring at any periodic period PR. This is done by introducing the following formulation.

First, a new variable is introduced, $BIAS_{pr,}$ which is equal to the difference between the capital baseline and the company’s actual capital costs (optimised by the model). $ROR_{wc,pr}$ is a binary variable and is equal to one when $BIAS_{wc,pr}$ is negative at the previous periodic review period (i.e. there is a ‘capital bias’) and equal to zero otherwise. This is done by introducing the following set of constraints:

$$-m(1-ROR_{wc,pr+1}) \le BIAS_{wc,pr} < mROR_{wc,pr+1} \quad \forall pr \in PR, pr > 1, wc \in WC \qquad 5.38$$

Variable $RCV\_ROR_{wc,pr,t}$ is equal to zero if there is a ‘capital bias’ (variable $ROR_{wc,pr}$ is equal to one) and equal to $RCV_{wc,t}$ otherwise. On the contrary, variable $RCV\_ROR\_B_{wc,pr,t}$ is equal to $RCV_{wc,t}$ if a bias occurs and equal to zero otherwise (equations 5.41 and 5.42).

$$RCV_{wc,t} - m(1-ROR_{wc,pr}) \leq RCV\_ROR_{wc,pr,t} \leq RCV_{wc,t} + m(1-ROR_{wc,pr}) \quad 5.39$$
$$\forall pr \in PR, pr > 1\,,\; wc \in WC$$

$$RCV\_ROR_{wc,pr,t} \leq m \times ROR_{wc,pr} \quad pr \in PR,\; pr > 1, wc \in WC \quad 5.40$$

$$RCV_{wc,t} - m \times ROR_{wc,pr} \leq RCV\_ROR\_B_{wc,pr,t} \leq RCV_{wc,t} + m \times ROR_{wc,pr} \quad 5.41$$
$$\forall pr \in PR, pr > 1,\; wc \in WC$$

$$RCV\_ROR\_B_{wc,pr,t} \leq m \times (1-ROR_{wc,pr}) \quad pr \in PR,\; pr > 1,\; wc \in WC \quad 5.42$$

In the equations above, m is a scalar. Term $[(io_t-i_t)\times RCV_t]=(\Delta ic\times RCV_t)$ in the profit equation 5.1, is now replaced by the following expression: $(\Delta ic\times RCV_{wc,t}|_{pr=1}+ \Delta ic\times RCV\_ROR_{wc,pr,t}|_{pr>1}-\Delta ic\_n\times\ RCV\_ROR\_B_{wc,pr,t}|_{pr>1})$. This parenthesis is referred to as $(\Delta ic\times\sum_t RCV_t)^*$ in Table 47 below. Term Δic_n is the difference between the allowed and the expected cost of capital. Δic_n is a negative number, while Δic is positive and set equal to 0.001 for the following model runs. This model run is referred to as 'Profit_neg_Δic'.

	Profit	Cost	Opex	Capex	CIS	IAJ	Δopex	$(\Delta ic\times\sum_t RCV_t)^*$
Δic_n=-0.01	480.5	1534	98	1436	248	46	107	99
Δic_n=-0.1	424	869	205	664	346	-	-	103

Table 47: Results from model 'Profit_neg_Δic'. Data are in M£ and are discounted to year 2010.

Results show that, if Δic_n is set to 0.01, the capital bias persists, due to the activation of a reservoir scheme in periodic review period PR19. The bias incurs in the periodic review PR14 and the company's return on the regulatory capital value becomes negative at the subsequent periodic review period PR24. This decreases the return on the asset base by M£ 18.5 without eliminating the bias. Only by decreasing Δic_n to -0.1, the capital bias is eliminated and the model returns the least-cost solution.

It is important to notice that, according to the formulation introduced in this section, Δic is set to a negative value every time a capital bias occurs ($BIAS_{pr}$<0) independently from the entity of the bias itself. As future work, a step function can be introduced in order to assign decreasing values of Δic_n (e.g. -0.001, -0.005, -0.01, -0.1, etc.) when the entity of the capital bias increases. Under such a formulation, the model may decide to reduce the bias without eliminating it completely (i.e. through the selection of lower-cost capital costs intensive schemes other than the reservoir schemes selected in this Chapter).

5.8.1.2 Exclusion of reservoir schemes

Since the 56% of the capital bias in 'Max Profit' is driven by the activation of reservoir schemes, their binary variables are now set to zero, in order to check how this would influence the capital bias. This model run is referred to as '*Profit_noRES*'.

Results show that capital costs are still higher than in the least-cost solution (by M£ 132) but lower than those (M£ 1597) in 'Max profit'.

	Profit	Cost	Opex	Capex	CIS	IAJ	Δopex	$(\Delta ic \times \sum_t RCV_t)$*
'Profit_noRES'	545	991	195	796	411	15	10	108.6

Table 48: Results from model '*Profit_noRES*'. Data are in M£ and are discounted to year 2010.

The model selects a change of occupancy metering scheme, which accounts for the 44% of total discounted capital costs (see Table 49) and increases the extent of use of aquifer storage and recharge schemes compared to the least-cost plan. Furthermore, an import scheme (set TR) is selected in place of a lower capital cost scheme of the same type, which was instead implemented in the least-cost plan (model 'Min Cost').

	Costs [£M]		
	'Profit_noRES'		
	Capital	Fixed operating	Weighted Variable operating
TR	179	67	83
ASR	136	13	14
ER	27	2	1
GW	23	8	0
DESAL	13	27	6
MET	349	4	-
SW	4	0	1
LEAK	25	-28	-
WEFF	40	-2	-
TOTAL	***796***	***89***	***106***

Table 49: Discounted capital, fixed and variable operating costs of schemes selected under model '*Profit_noRES*'.

5.9 Discussion

The 'Max profit' model has limitations, which relate to the formulation itself and its application as listed below:

1. The company regulatory capital value (RCV) calculation is approximated. 'Grants and contributions' are included in the RCV as input data obtained from interpolation of

historical data. The ‘infrastructure renewal charge’ and the depreciation for the existing infrastructure assets are also estimated through projections of historical trends. The retail price index, used to adjust at each periodic review the RCV by the inflation, is also estimated. Only non-infrastructure assets (e.g. reservoirs, transfers) are depreciated (by dividing their capital expenditure by their useful life, as explained in the Ofwat report ‘The approach to depreciation for the periodic review 2004-A consultation paper’). The model only optimises the capital and operating expenditure to maintain and enhance the network (i.e. it returns the portfolio of supply-side schemes and demand management measures that meet forecast demand levels). The difference between the infrastructure renewal expenditure and the infrastructure renewal charge is hypothesised to be equal to zero.

2. The calculation of the CIS incentives is approximate: the allowance on the capital expenditure (the ‘baseline’) is estimated from companies’ June returns. The CIS ratios are from (OFWAT, 2010b) and are considered constant over the planning horizon.

3. Not all costs (e.g. quality enhancement, customer service) are optimised by the ‘Max Profit’ model, but only those relative to the capacity expansion problem (i.e. to enhance the network). The ‘non-optimised’ costs are introduced as input parameters, obtained by interpolation of historical data from the June Reports. This however does not change the model concept, as the scope of this work is to show, based on schemes’ costs, which kind of expenditure (if capital-cost based or operating-cost based) is selected by the model in order to maximise companies’ profit.

4. There are other mechanisms used by Ofwat to incentivise companies to manage costs that are not represented in the model formulation. These include: ‘shortfalling’ according to which companies’ revenues are further reduced in case of non-delivery of the required outcomes (e.g. quality and legal obligations), ‘interim determination’ and ‘logging-up’ (or ‘logging-down’) to account for any reasonable additional (or reduction) in cost caused by changes in the sector legal obligations. This means that the regulatory process is dynamic: changes are allowed in between review periods, and this is not represented in the model. Also, there are regulatory incentives concerning the quality of the service (customer service, environmental performance such as pollution incidents, water quality, etc.), referred to as the OPA and SIM incentives, that are not represented in the model. However these can only impact companies’ revenues by the 0.5% to -1% (OFWAT, 2010b).

5. The conservatism or risk aversion behaviour of companies (some investment choices by decision makers are based on “gut feelings” about what works in the field or is more politically acceptable) is not represented in this work; this may also contribute to a ‘capital bias’, as explained subsequently. Water companies may see operating costs solutions as ‘more risky’ than capital based ones because of the different certainty of delivery of the two cost types (for example the success of a water efficiency programme depends on customers’ habits and reactions, which may be difficult to predict). Water companies may also have a preference to use their own assets, such as reservoirs, in place of operating based solutions like imports from neighbouring areas. Also, water companies and investors may focus on the growth of the regulatory capital value as a metric that represents the company’s growth (Ofwat, 2011). This is because the RCV provides a measure of the company’s ability to remunerate investors for the investment programmes on long-life assets. Finally, the ‘relative efficiency scheme’ on the operating costs may also contribute to form a ‘capital bias’; Ofwat publishes each year ‘league tables’ setting out information about the relative performance of each company. Such estimates are incorporated in the operating expenditure allowance included in price limits. This incentive is applied to the operating costs only, since the CIS scheme is used for the capital costs in order to set expenditure assumptions. Under the ‘relative efficiency incentive’ scheme, companies may see an increase in the operating expenditures as something that would worsen their position in the Ofwat’s ‘league table’ (Ofwat, 2011). For this reason, in order to decrease the operating costs, they may opt to replace operating cost intensive solutions with capital cost based ones.

6. The utility profit maximising model ‘Max profit’ is applied to individual water companies without considering exports. Imports are allowed but do not take account of the supply-demand balance situation in the exporting company. Future work could be done to address this limitation and introduce interactions between companies, using decentralised optimisation (Yang et al., 2009, Berger, 2001, Berger et al., 2007) or game theory methods (Mahjouri and Ardestani, 2010, Wang et al., 2003, Wang et al., 2008).

7. The ‘Max profit’ model uses public data from company water resources management plans (WRMPs). Since costs in the WRMP tables are in net present value, several hypotheses were made to extrapolate the undiscounted cost figures from the net present values. The approximate cost estimates are why the study results cannot be used to

evaluate specific infrastructure investment decisions but can only give insight about what scheme types are selected based on their declared capital and operating costs.

8. Finally the model does not include taxes in the estimates of companies' revenue requirement, i.e. its does not consider the fact that companies need to pay corporation tax on profits. The tax allowance includes the so-called 'capital allowances' available under UK tax law. According to the 'capital allowances' scheme, when any company spends on certain types of capital assets (e.g. long life assets, industrial building allowances, etc. (see (Ofwat, 2009a) for a complete list), it can use a part of that cost to lower its taxable-profits in the early years. This means that the company can claim the cost as a tax allowance early in the life of the asset instead of only getting that tax relief later and over the whole life of the asset through a depreciation amount. This reduces the company early years' corporation tax bills and brings forward the profile of shareholder-profits expected to be earned on the capital expenditure. If the investors prefer early profit to later profit, the tax allowances may have an incentive effect to make investments in the capital expenditures. The 'financial model rule book' (Ofwat, 2009a) shows in detail how Ofwat models taxes including the 'capital allowances' scheme.

Given the limitations listed above, the model presented in this Chapter does not claim to be able to precisely quantify the 'capital bias'. The model is meant to investigate if, under the current set of regulatory incentives, a 'capital bias' effect could occur and why. Such bias is revealed by running the 'Max Profit' model and by comparing its results (schedule of schemes) with those obtained if companies were simply minimising the cost of future capacity expansions (model 'Min Cost'). The 'Max Profit' model presented here cannot embed all of the complexity of the regulatory framework, however it does represent how companies can make profit under the current set of regulatory incentives. This can occur by companies outperforming the regulatory assumptions of the costs of capital and on the operating costs, and through rewards/penalties for out- or under-performances on the operating and capital expenditures.

As future work, further changes to the model formulation could be made to investigate how different regulatory practices impact the 'capital bias'. Such changes could include a cost recovery approach that eliminates the distinction between the capital and the operating expenditures. The 2015-20 regulation in England is already considering this by allowing a determined ratio of companies' total costs (capital plus operating expenditure) to be remunerated through the companies' regulatory capital value. The remaining portion of the companies' total costs will be recovered in the year the costs are incurred. Also additional incentives will be introduced to encourage water companies to trade (Ofwat, 2013d). Another different regulatory practice could be to allow a return on the operating expenditures in addition to the return on the regulatory capital value. Then if, as a result of this option, costs are still higher than the one in the least cost solution, the rate of return on the operating expenditure could be adjusted to leave the two returns in neutral present value terms (Ofwat, 2011). Such a strategy could be implemented by setting the allowed rate of return on the operating costs as a decision variable optimised by the model. In addition, incentives on the total expenditure could be allowed rather than separate incentive schemes on the capital and operating costs. This could be implemented by setting term $\Delta opex$ equal to zero (so that out- or under-performances on the operating costs do not affect the company's profit), and by replacing the CIS scheme (for capital expenditure) and the rolling incentive allowance scheme IAJ (for the operating expenditure) by a new incentive scheme on total costs (capital plus operating costs). Finally the model can also be used to test whether incentives with rewards and penalties or penalties only should be allowed.

5.10 Conclusions

A capacity expansion optimisation model was formulated to simulate how the 2010-2014 price cap regulation (referred to as PR09) influences natural monopoly water utility investment plans in England. The model identifies the annual schedule of scheme implementations (supply, demand management, and transfer options) that meet future demands and maximise companies' profits under social, environmental and regulatory constraints. English water companies can make profits by outperforming the cost of capital and lowering the operating expenditures below the regulatory allowance. When companies invest in capital schemes, the associated expenditure is added to their regulatory capital value increasing the return that they can earn on it; no such return is earned on operating expenditures. All of this is represented in the model formulation together with the regulatory incentives for costs savings. Such incentives include the CIS scheme for the capital expenditure and the rolling incentive allowance for the operating expenditure (opex). The model formulation also considers the length of the price control period: the planning horizon is split into slots of five years; decisions (what to activate, when and at what capacity) are optimised over the whole planning horizon, however the regulatory incentives (the rolling incentive allowance and CIS rewards/penalties) are optimised based on the periodic review period.

Results from the utility profit maximising model are then compared with the least-cost capacity expansion plan (social optimum). This plan represents the ideal scenario of the cost efficiencies that could be achieved if, under the 2010-14 regulatory constraints, companies are incentivised to minimise the total cost of future capacity expansions. The comparison shows that under the utility profit maximising model, capital cost based schemes, such as reservoirs, are activated in place of some of the operating cost based schemes, such as transfers, selected in the least-cost solution. This shows that under the current set of regulatory incentives (utility profit maximising model) companies make profit by increasing the capital expenditure over the operating costs. Such phenomenon is known in the English water sector as ‘capital bias’. Sensitivity analysis is applied to the utility profit maximising model to gain insights about the causes for the capital bias. The fact that companies accrue one hundred percent of any underperformance on the operating expenditure, may induce them to replace opex-based solutions with options that are capital-based ones. This distortion could be reduced through financial penalties by using the CIS scheme. However, since the CIS scheme allows for a symmetric treatment of the capital expenditure (both rewards and penalties are allowed for out- and under-performances), a company may still opt to increase the size of its regulatory capital value (by incurring capital expenditure), through a combination of CIS rewards/penalties that balance out over time. Furthermore, the extent to which a company can outperform the regulatory assumptions on the cost of capital can also increase the ‘capital bias’ effect. Results show that by increasing the gap between the regulatory allowed and the company’s actual cost of capital from 0.001 to 0.01 the capital expenditure in the model solution increases.

The model formulation was extended to examine the case in which the allowed cost of capital is lowered below the actual cost of capital, for any periodic review period after the one where a ‘capital bias’ is recorded. Sensitivity analysis is conducted where different values were assigned to the negative difference between the allowed and the actual cost of capital (i.e. the return on the company’s regulatory capital value). Results show that by decreasing the company’s rate of return, the ‘capital bias’ could be removed. Since the return on the asset base is given in input to the model independently on the entity of the capital bias, the model identifies solutions where the capital-bias persists or is eliminated. As future work, a step function could be introduced in the model formulation in order to assign decreasing values to the return on the asset base as the entity of the capital bias increases. Under this formulation, the model will have the incentive to identify solutions where the capital-bias is reduced without being eliminated. Results show that the return on the asset base plays a significant role in generating or decreasing the capital bias. However, this leads to the following question. To what extent can the regulator can the allowed cost of capital below the company's actual cost of capital, in order to reduce (or remove) the bias? This is because when setting this vale, the regulator has to ensure that the water company will be able to finance its investment programme.

This Chapter also discussed elements of the PR09 regulatory systems which are not represented in the model, but that may still contribute generating a 'capital bias'. For example, the companies' conservatism and risk adverse behaviour, not represented in our model, can also contribute generating a 'capital bias'. Finally, it discusses the UK tax allowance system that includes the so-called 'capital allowances' according to which any time a company spends on certain types of capital, it can use a part of that cost to lower its taxable-profits in the early years. This could also contribute towards capital-biased solutions. No such allowance is designed for the operating expenditure.

The Chapter concludes by analysing potential changes in the 2010-14 regulation to address the 'capital bias' effect. Such changes include incentives on total costs rather than on the operating and capital expenditures. In general, the least cost solution (see model 'Min Cost') is given by a determined ratio of capital and operating costs and the relative strength of the incentives that the regulator placed in the two cost types (capital and operating expenditures) may induce companies towards bias preferences for capital cost intensive solutions. Benefits and limitations of the proposed model formulation and its application are also discussed.

Chapter 6

CONCLUSION

6 Research statement

The expectation of reliable water supplies to support economic development and social stability is growing worldwide. In England some regions will likely face intermittent and increasing water scarcity due to risings population and possibly climate changes. Maintaining the supply-demand balance is a priority for the nation's private water companies and their financial and environmental regulators. Water companies face the challenge of scheduling new supply infrastructure investments to maintain the supply-demand balance at minimum cost. Regulators are also interested in minimum cost capacity expansion planning, as this is one way they evaluate and regulate proposed water company schemes. Since over a decade water companies in England follows the 'Economics of Balancing Supply and Demand' (EBSD) framework for capacity expansion (UKWIR, 2002a, UKWIR, 2002b); The EBSD framework has some clear benefits that explain its wide application to the English water sector such as its applicability to large scale systems with complex interdependencies and institutional appropriateness (the framework provides the output that regulators require). Furthermore, EBSD determines the least-cost combinations of schemes to meet future demands but also the least-cost investment scheduling over a multi-year planning horizon. Given the challenges faced in real-word capacity expansion problems (Fiering et al., 1986), the fact that EBSD is used to justify infrastructure investments nation-wide, is a demonstration of its success. However, as any modelling, the EBSD framework and its application in practice are not exempt from limitations. These have motivated this thesis research which is summarised in the following section.

6.1 Thesis contributions

Past applications of the EBSD framework did not consider, or not in a sufficient detail, demand management measures (water conservation). Because demand management may be a cost effective and environmentally beneficial way to establish the supply-demand balance, it is recommendable to expand EBSD models to represent such options.

Many EBSD models do not deal rigorously with infeasibilities which inevitably arise in real-word applications when the available supply is lower than forecast demands. This might result from unexpected imposed reductions on supply for environmental protection reasons, or due to constraints on the availability of new resources. Work in Chapter 2 addressed both of these issues. An optimisation model formulation following the EBSD framework was proposed and applied to a large-scale regional system in the South East of England (the WRSE area). Demand management schemes were included in the capacity expansion portfolio model and ad-hoc constraints were introduced to allow for user-defined saving profiles accounted from the schemes' first year of activation. A two-step optimisation procedure was also implemented to eliminate model infeasibilities. The procedure reduces demands at infeasible areas just enough to ensure a feasible supply-demand balance condition can be restored (and informs analyst to which supply zone the demand had to be manipulated so that more options can be added in these zones). Model infeasibilities could also be removed by injecting flow at infeasible areas at high penalty costs. However, penalty costs can make the model less sensitive to real schemes costs and lead to sub-optimal results.

The model in Chapter 2 was further expanded in Chapter 3. A new formulation was presented that allows incorporating a generic capital cost estimate through a concave cost curve approximated by a piecewise linear function. This allows expanding the WRSE network with additional nineteen potential inter-company transfers not proposed in company plans. Model results showed that a potential net present value cost saving of about £1 billion could be achieved over a 26 year planning horizon from increasing the level of water supply interconnectivity in the region. This was achieved primarily because several supply-side sources or expensive demand management options were replaced by relatively lower-cost interconnections.

Work in Chapter 4 was conducted to overcome difficulties faced by the English water sector around the application of a stochastic version of the EBSD approach, called the 'intermediate framework'. The 'intermediate framework', by re-evaluating companies' headroom values, has led to some confusion which has generally discouraged its application. This is because companies' headroom estimates follow an already established regulatory guideline (UKWIR, 2002a, UKWIR, 2002b). Furthermore the 'intermediate framework', by adjusting companies' headroom values, may create network infeasibilities if the increased level of demand (distribution input plus the new headroom values) becomes higher than the available existing and new supplies. In this case the ‘intermediate framework’ cannot be run to completion. Furthermore, since increasing the headroom values triggers the EBSD model to activate new schemes, the ‘intermediate framework’ can overlook lower cost solutions that are still reliable. This may discourage its application in a regulatory context where water companies must justify to the regulators that their plans are at least-cost. These limitations were overcome by the proposed approach. This approach does not modify the headroom values, but uses ad-hoc constraints to exclude unreliable solutions identified in previous iterations. The ‘*CUT-strategy*’, contrarily to the ‘*THR-strategy*’, returns the lower-cost reliable solution. An extension of the ‘*CUT-strategy*’ is also presented that allows identifying a diverse set of reliable portfolios in addition to the least-cost one. Since EBSD models are single-objective (i.e. it require monetising all aspects of system performance) and given the uncertainty of scheme projected costs, the least-cost solution may not be the ‘best’ solution to a problem. It is therefore important to provide company decision makers with a set of reliable near-optimal solutions in addition to the least-cost one (see also Appendix II).

Work in Chapter 5 presented a modified capacity expansion formulation that maximises water company profits under constraints on their allowed rate of return and the maximum price that can be charged to customers. The regulatory incentives for costs savings were also represented; these included the CIS scheme for capital expenditure and the incentive allowance schemes for the operating costs. The aim of this work is to help understand how companies’ investment decisions could be influenced by the current regulatory regime, and explore the causes for what the sector calls the ‘capital bias’ effect, i.e., companies’ preference to capital based solutions in lieu of more cost-effective schemes that are operating expenditure based. The model’s results were compared with the least-cost solution obtained by running, for the same company, the social optimum EBSD model introduced in Chapter 2. The comparison showed that a ‘capital bias’ effect can be generated mainly because the regulator places separate incentives on capital and operating expenditures. Since companies are liable for one hundred percent of any under-performance on the operating expenditure, they may be encouraged to reduce the operating costs and opt for schemes that are more capital cost-based. The ‘capital bias’ may also depend on the extent to which a company can finance its investments at a rate below the allowed cost of capital. Results showed that by increasing the out-performance on the cost of capital, the capital bias effect increases. CIS rewards/penalties can reduce the capital-bias, however a company may still opt to maximise the size of its regulatory capital value (on which a return is earned), through a combination of rewards/penalties that balance out over time. If the difference between the allowed and actual cost of capital (i.e. return on the company asset base) is lowered to a negative value, for any periodic review period after the one a capital-bias occurs, then the capital bias may persist of be removed. This depends on the extent by which the return on the company asset base is decreased. However, this raises the question of whether such strategy could be applied to remove the bias, given the fact that the regulator has the duty to set an allowed cost of capital so that the company will be able to finance its investment programme.

Further extensions to the EBSD framework are presented in Appendix I and II. In Appendix I the EBSD model in Chapter 2 is extended to allow scheme costs to be accounted over their whole useful life, beyond the 25 to 30 year planning horizon. This is done to avoid biased comparison of schemes with varying economic lifetime. In Appendix II the EBSD model in Chapter 2 is expanded to generate multiple near-optimal solutions. It is argued that, since EBSD models are single-objective (all aspects of system performance are monetised) a 'nearly' optimal plan may be preferred by company decision makers and regulators if it presents non-monetary benefits that cannot be represented in EBSD models. The near-optimal solutions are displayed in parallel axis plots to show their diversity in terms of frequency of selection, extent of use, and timing of scheme activation. The near-optimal plans are diverse; for example, the optimal capacity of reservoir schemes and imports varies as much as 520% and 415% respectively. Results show that by allowing costs to deviate by just a few percentage points from the least-cost plan, solutions can be found with a high diversity in terms of schemes' selection and extent of use. For example, a plan 6% more expensive than the least-cost one is identified that uses reservoir schemes at a 24% higher extent and import options at a 30% lower extent than in the least-cost plan. For a decision-maker not trusting the potential gains of imports and demand management schemes, this would be a tempting plan to adopt. Generating near-optimal solutions also allow identifying schemes that possibly represent low-regret decisions (if selected in many of the near optimal plans). Finally, near-optimal solutions can be identified that allow company decision-makers to avoid or delay the implementation of schemes that present political or environmental challenges.

6.2 Discussion of limitations of each technical Chapter and future work

There are still issues related to the EBSD framework that needs to be further explored. Some of these relate to the underlying structure of the capacity expansion problem as formalised by the EBSD planning framework and are listed below:

1. The problem of non-convex cost functions in capacity expansion is overcome by a significant compromise: fixing capacities and costs into proposed discrete schemes rather than using continuous cost functions. Given each discrete option generates a computationally expensive binary variable, inevitably too few discrete possible capacity and costs values are included, a limitation which necessarily leads to the sub-optimality of suggested 'least-cost' plans. This limitation is partially mitigated by the fact that water companies and regulators prefer costing discrete schemes as they are unwilling or unable in many instances to generate continuous cost curves, which in practice for large systems are not always easy to generate reliably. In Chapter 3 the use of non-convex costs curves is allowed for a set inter-company transfers.

2. In EBSD models, yields of all schemes are estimated separately by water companies by running a simulator under historical drought conditions. This may work well for hydrologically independent supplies like desalination, but ignores possible interactions between schemes (such as stream-aquifer interaction or combinations of demand management schemes) which could imply that the yields ('deployable outputs' of sources) are inaccurate, particularly under stressed conditions where hydrological systems tend to act non-linearly;

3. In areas where over-year storages plays a significant role in water supply, it may be inappropriate to assume each year supplies are unrelated to previous year's storage levels and that there is no hedging in consumption in response to low storage in multi-year storage facilities. In this case more complex formulations that track storage levels and other water management variables, e.g. at the monthly level, can be necessary (Loucks et al., 1981);

4. The EBSD model is single objective, whereas real water supply systems are managed according to several criteria (such as reliability, energy use, etc.). Generating multiple near-optimal solutions (see Appendix II) gives an idea of what alternative plans are available in addition to the least-cost one. This increases the freedom for planners to

consider un-modelled factors and other strategic priorities in the decision making process. However, even if multiple near-optimal solutions are considered, no quantitative approach is provided to assess how these solutions perform with respect to other non-monetary criteria (e.g. resilience, environmental performance, etc.) that may be important to decision makers. A multi-objective model formulation would allow optimising other societal/water company objectives and generating multiple plans whose performance can be assessed against the optimised objectives.

5. The 'intermediate framework' uses Monte Carlo simulation to test the reliability (probability of failure) of the EBSD model solution if the deterministic supply and demand estimates are subject to uncertainty. There are however uncertainties that cannot be analysed by Monte Carlo simulation. The root cause of this type of uncertainty is not the random variation of parameters, but a more fundamental lack of knowledge or understanding of complex dynamic interactions involving non-linear feedbacks within the system, or unpredictable system responses to unknown future conditions (e.g. the effect of climate change on the system hydrology or the impact of future socio-economic forces). In presence of unreliable predictions due to deep uncertainty (Lempert et al., 2003) decision makers could seek 'robust' actions that are stable under a wide range of future conditions. Robust optimisation could be used to identify solutions that are less sensitive to data variations and remain stable under different possible scenarios, but this is not considered in the EBSD framework.

In addition to the limitations above, the extensions proposed in each Chapter have their own limitations which are discussed below.

In Chapter 3 a non-convex cost curve was used for inter-company transfers that are not yet proposed by water company plans. The curve was approximated by a piecewise linear function which increased the model computational burden.

In our application, the 'branch and bound' commercial solver did not converge to global optimality, but returned a solution that may distance from it by up to 28% in cost. Also, since the model is applied at a regional level, it cannot accurately represent companies' willingness to engage into transfers with neighbour water companies. Because the companies are independent, the effect or inefficiency of institutional rules and transaction costs would also need to be considered to approximate the gains that are possible from regional inter-connections.

In Chapter 4 a new modelling approach was proposed in order to overcome limitations of the stochastic version of the EBSD framework called the ‘intermediate framework’. The new approach was applied to a pilot network composed by three water resource zones. A limitation of this approach is that it may require a higher number of iterations to converge to a solution compared to the ‘intermediate framework’. The number of iterations possibly increases with the dimension of the network. This means that, if the new approach was applied to a larger network, composed by a higher number of schemes, the total run time could possibly increase considerably.

In Chapter 5 a new EBSD-based model formulation was developed to analyse the impact of the English 2010-14 price-cap regulation on companies’ investment decisions. The proposed model only optimises investment decisions that are related to the capacity expansion problem. Other expenditures, such as costs for quality enhancement or to improve customer service, were obtained by interpolation of historical data. This means that the regulatory incentives placed on the non-optimised expenditures (the OPA and SIM schemes), could not be represented in the proposed model formulation. However, such incentives can only influence companies’ revenue by the -0.5% to 1% (OFWAT, 2010b). Furthermore, the model does not represent companies’ risk adverse behaviour (some investment choices are based on gut feelings about what works in the field or is more politically acceptable), as well as companies desire to engage in transfers (the model is run at a company level and imports from external areas are considered through discrete schemes). Given these limitations, the model results probably cannot yet be used to fully explain ‘capital bias’ in the regulated system. The model does however represent how companies in England are allowed to make profits: by out-performing the regulatory allowance on the rate of return and through a system of rewards/penalties for out/under-performances on the capital and operating expenditures. The model can therefore be used to help explain how the current regulatory system of incentives may motivate a ‘capital bias’ on water company investments. Future work could test how different regulatory practices impact the ‘capital bias’. For example, the new 2015-20 regulation could be modelled and compared with other possible regulatory practices. The 2015-20 regulation in England will allow companies to remunerate a determined ratio of their total costs (capital plus operating expenditure) through the regulatory capital value. An alternative regulatory practice could be to allow companies to earn a separate return on the operating expenditure, in addition to the return on the regulatory capital value (that only includes the capital expenditures). In order to leave the company neutral towards the two cost types, the rate of return on the operating expenditure could be adjusted to leave the two returns in neutral present value terms. In addition to this, incentives on companies' total expenditure (capital plus operating costs) could be applied rather than separating the two cost types. We leave these investigations to future work.

Despite several limitations, the benefit of the applied model and EBSD framework are their relative simplicity and applicability to large systems with complex interdependencies. Although water supply planning of large populous regions is complex, this framework parsimoniously boils the problem down to its most essential components to cost-effectively address the regional supply-demand planning problem for real-world systems. Not only does the model find the least-cost mix of schemes, but recommends the least cost implementation schedule to meet projected demands as well. The fact that the model formulated here is being used in a regulator-led effort to optimise investments for South East England with 17.6 million inhabitants is a testament to its ability to help plan real systems.

6.3 Discussion on results obtained from applying the capacity expansion models to the South East of England

In Chapter 2 and Chapter 3, the capacity expansion model developed in this thesis, was applied to identify regional least-cost investment decisions in the South East of England. The networks in Chapter 2 and Chapter 3 refer to the South East area, however they differ in their topology and input data. Specifically, the one in Chapter 2 uses private data from the 2013 water company resources management plans, while the one in Chapter 3 uses water companies' public data available online.

Results obtained from running the model in Chapter 2 show that the inclusion of demand management schemes reduce costs by 6% (£M 68) over the 25-year planning horizon. In Chapter 2, water company proposed transfers (referred to as LFT), reduce total discounted costs by 67% (i.e. from £M 1445 if no transfer is allowed to £M 981 otherwise). Similarly, in Chapter 3, discounted costs decrease by 1.2%, i.e. from £M 2259 if no company proposed transfer is allowed, to £M 2232 otherwise. The lower reduction in costs in Chapter 3 (1.2%), compared to the 67% reduction in Chapter 2, is due to the lower number of transfers (i.e. 21) compared to Chapter 2 (i.e. 215). Furthermore, out of the five selected schemes in Chapter 3, four of these represent extensions in time of existing bulk transfers and do not have capital costs associated.

When 19 additional transfers are included in the network in Chapter 3 (to interconnect water resource zone in surplus to the neighbouring ones in deficit), total discounted costs decrease by 47% (i.e. from £M 2232 to £M 1178, which corresponds to a total saving of £M 1053). If the number of transfers is increased from 19 to 92 (to interconnect all neighbouring water resource zones belonging to different water companies), only a 28% relative gap solution can be achieved in 14 days run. The 28% gap solution, however, has M£ 147 total discounted costs, considerably lower than £M 1178. The 92 transfers allows therefore identifying convenient chains of interconnections within the network (these also include intermediate interconnections between water resource zones in surplus, or from a zone in deficit to another in surplus). A better solution can therefore be achieved, than if 19 transfers only were considered, even if this has 28% relative gap.

Results also show that the 43% (Case 2, Chapter 2) and 43% (‘*full-INT*’, Chapter 3) of total costs in the South East of England are due to the activation of schemes in the London water resource zone, the one with the highest deficit in the whole network.

Results from Chapter 3 suggest the implementation of imports from areas with a higher extent compared to other scheme types. For example, a bulk sea import from Norway is activated that generates the 20% to total discounted capital costs in the London area. In contrast, Chapter 2 suggests the activation of two effluent reuse schemes in the London zone, which generate the 27% of the total discounted capital costs. Specifically, one has a maximum annual capacity of 150 Ml/d (i.e. it provides 33% of total supply from selected schemes in the dry year critical period scenario), the other one of 60 Ml/d. No import scheme is available in the London zone that can provide 150 Ml/d.

The selection of effluent reuse schemes or imports depends therefore on the zone level of deficit and availability of schemes. For example, in Chapter 3, the import from Norway provides a maximum annual capacity of 214 Ml/d. The scheme with the second highest level of supply in the London area is an effluent reuse option with a 100 Ml/d capacity (apart from another import that is mutually exclusive to the selected one). If the 100 Ml/d effluent reuse scheme were selected in place of the import from Norway, the activation of another option would have been necessary to reach a total capacity of 214 Ml/d. This would have increased the total cost of the solution.

Even if in Chapter 2 effluent reuse schemes provide the highest level of supply amongst selected supply-side options in the London area, the second largest volume (368 Ml/d over the planning horizon, i.e. 10% of supply from selected supply-side options) is generated by an import scheme. This confirms, once again, that imports from external areas represent an important solution to the supply-demand planning problem. When the major effluent reuse schemes in the London area are deactivated, then a surface water scheme is selected which provides 18% of supply from all optional schemes (i.e. 1006 Ml/d in the dry year annual overage scenario). Therefore, surface water schemes also represent an important solution for the capacity expansion problem.

Finally, in both Chapter 2 and Chapter 3, demand management options highly contribute to the supply demand balance (i.e. by 25% in Chapter2 and 23% in Chapter 3, under the dry year critical period scenario). Amongst these, leakage schemes are the one that provide the highest level of savings (i.e. 85% in Chapter 2 and 95% in Chapter 3).

6.4 Assessment of the methodological approach

This thesis developed capacity expansion optimisation models by using mathematical programming techniques (i.e. mixed integer linear programming, MILP). The MILP models are solved with CPLEX. CPLEX uses the branch and bound algorithm which adopts an iterative procedure to find a solution to the capacity expansion problem. At each iteration (‘node’), the algorithm identifies an upper bound solution (integer solution in the case of cost minimisation, also referred to as ‘incumbent’) and lower bound one (where all binary variables are ‘relaxed’ to continuous values). The algorithm stops it search when the difference between the upper and lower bound solutions divided by the incumbent (i.e. the relative gap), is lower than the user pre-defined tolerance (i.e. 5%).

The capacity expansion model developed in this thesis returns solutions with relative gaps lower than 5% when applied to small networks (Chapter 4 and Chapter 5). When, however, the network dimension increases (e.g. South East of England in Chapter 2 and Chapter 3), the computational burden also increases. Specifically, in Chapter 2, the model reaches a 2.76% relative gap in 30 hours if demand management options are not included, and a 5.9% relative gap in 45 hours, when 511 demand management schemes are considered. The 511 demand management options add 12,775 binary variables (i.e. 511 multiplied by the 25 years of the planning horizon) and 76,650 constraint equations.

Inter-regional transfers are the one that affect more than other scheme types the model computational burden. When all transfers are excluded from the network a 1.93% relative gap in reached in 3.5 hours in Chapter 2 and a 1.5% one in less than 20 minutes for Chapter 3. The computational burden considerably increase when the network is expanded with additional transfers not proposed yet in water companies' resources management plans. For these transfers, capital costs were represented through a piecewise linearised non-convex function, using a set of variables called 'special order set of type 2'.

When additional 19 transfers are considered (to interconnect water resource zones in surplus to those in deficit only), the model cannot reach a relative 'gap' lower than 5% in 12 hours (without the 19 additional links, a 3.3% relative 'gap' is reached in the first 30 minutes). Increasing the network by 19 transfers corresponds to including additional 475 binary variables (19 multiplied by 25 years), 76 SOS2 variables (19 multiplied by the 4 breakpoints of the piecewise linear problem) and 19000 new continuous extent of use variables (19 multiplied by 25 years and by 4 as the number of demand scenarios). If then, the number of links is increased from 19 to 92 (to interconnect all neighbouring water resource zones belonging to different water companies), the model can only converge to a 28% relative gap in fourteen days. With a fully interconnected network (i.e. 137 links are added to interconnect all neighbouring water resource zones), the branch and bound algorithm cannot even identify an integer solution. Considering 137 links raises a hard combinatorial problem that requires an exhaustive enumeration. For any additional link, the binary variable can be either zero or one at any year *t* of the planning horizon. For any of these combinations, a convex optimisation problem is created. With 137 links and 25 years, the number of possible problems is prohibitively high (i.e. 25×2^{137}).

Initial solutions were given in input to the models in Chapter 2 and Chapter 3, without being able to improve the models convergence. This implies that setting the initial solutions to aid convergence may not be appropriate for EBSD models.

In general, the analysis of the upper and lower bound solutions in Chapter 2 and Chapter 3 reveals that the branch and bound algorithm has a fast convergence only at the beginning of the running time. For example, in Chapter 2, when demand management schemes are not included in the optimisation problem, the upper bound solution decreases from £M 103 to £M 100 after 4.5 hours and a second improvement from £M 100 to £M 981 is recorded after 13 hours. Then, the upper bound solution does not improve considerably over the remaining running time. Similarly, the lower bound solution increases from 947 to 1005 within 1.3 hours, but then it does not improves considerably over the remaining running time. A similar trend is observed when demand management schemes are included, and for the models in Chapter 3.

In all runs, the closure of the gap between the lower and upper bound solutions recorded towards the beginning of the running time, is not repeated afterwards: the upper and lower bound solutions do not improve significantly as the running time increases. Specifically, the amount by which the difference (gap) between the upper and lower bound solutions is decreased at the beginning of the running time, is greater than the gap that remains afterwards. This suggests that there is no reason for increasing the running time once the gap is reduced by an extent that cannot be further repeated.

6.5 Conclusion

This thesis has developed and applied a capacity expansion model formulation to support investment decisions in the water supply sector. The starting point was the 'Economics of Balancing Supply and Demand' (EBSD) framework used by water utilities in England since 2002. Several extensions to the EBSD framework were presented with the objective of assessing and improving upon some of its limitations.

Firstly, user-defined savings profiles for demand management schemes were allowed and a two-step optimisation process was developed to manage network infeasibilities that inevitably arise in real word applications. Then, a new model formulation was proposed that allowed expanding companies' networks with additional inter-company transfers. Costs for such transfers were described by a non-convex curve approximated by a piecewise linear function. Subsequently, an extension was proposed to improve the application of the 'intermediate framework'. The proposed approach consists of running the EBSD model iteratively and testing the reliability of the solutions with Monte Carlo simulation. To ensure that different supply-demand schedules were generated at each run, special constraints were used to eliminate unreliable solutions identified at previous iterations. Next, a new EBSD based capacity expansion model was presented that maximises companies' profit under the 2010-14 regulatory framework in England. The aim is to understand if the current set of regulatory incentives may be causing a 'capital bias', i.e., a preference towards capital based solutions in lieu of more cost effective schemes that are operating expenditure based. Finally Appendix I presents an extension of the model formulation that allows scheme costs to be accounted for over the schemes' lifetime when they extend beyond the planning horizon. In Appendix II multiple near-optimal solutions are generated in addition to the least-cost plan. Generating multiple near-optimal plans allow decision-makers to more easily consider non-monetised criteria and strategic priorities that cannot be represented in EBSD models.

Future research could be focused on improving the EBSD models to represent interactions between companies, such as transfers. In this thesis, the EBSD model was applied to individual companies or to a regional system where all water companies are combined (a single regional objective function is used). Results therefore represent the best case scenario of the cost efficiencies that can be achieved. However, because companies are independent, the inefficiencies of institutional rules and transaction costs would need to be considered to approximate the gains that are possible.

Further work is also needed for the regulatory model presented in Chapter 5. Further analysis will be carried out to understand how changes to the 2010-14 regulatory framework presented in Chapter 5, could impact the 'capital bias'. Regulatory changes include replacing the current set of incentives for cost savings on capital and operating expenditures with incentives on the total costs (capital plus operating). The new 2015-20 regulation may also be represented, by allowing companies to recover a determined ratio of the total expenditure (operating plus capital costs) through their regulatory capital value.

Finally, general EBSD framework limitations were identified that need further exploration. EBSD models are single objectives, i.e., all aspects of system performance are monetised which means that important non-monetary metrics of system performance (such as resilience, environmental performance, etc.) cannot be represented in the model. Also, EBSD uses hydrologically independent estimates of supplies, i.e., firm yields are estimated through external simulators based on historical drought conditions. This means that complex interactions between schemes cannot be represented, which can be significant for groups of schemes working together, using various operational triggers (such as stream-aquifer options). In addition to this, EBSD models do not consider over-year storage levels, i.e., supply in each year is assumed to be unrelated to previous year storage levels. This means the EBSD approach is not appropriate for regions where reservoirs are used to store water from one year to another. Finally, the stochastic version of EBSD uses Monte Carlo Simulation to test, under random variations of supply and demand data, the reliability (frequency of failure) of the supply-demand schedules selected by the model. However, when the cause of uncertainty is not limited to the random variation of parameters but is due to a lack of understanding of the system behaviour and unpredictable responses to future conditions (global change, future socio-economic drivers), stochastic optimisation could be used to identify plans that are robust as remain stable under a wide range of possible scenarios. The conclusion Chapter also provides an assessment of the methodological approach used in the dissertation and a broad analysis of the results obtained by applying the proposed models to the whole South East of England.

Because the EBSD framework is a relatively simple approach for supply-demand planning that has been applied nationally in England for over a decade, it will likely continue to be used for some time; therefore, this thesis has made a substantial contribution to the field by investigating its limitations and possible extensions.

Appendix I- Extension: accounting costs over their useful life

EBSD models typically make investment decisions over a 25 to 30 year time horizon (UKWIR, 2002a, UKWIR, 2002b), with costs also accounted within that period. This means that the assets' residual costs, i.e. the costs to keep the assets functional beyond the planning period, are not accounted; this may create biased comparisons among schemes (see also section 1.6.2.6). Recent guidelines from the Environment Agency (EA et al., 2012a, EA et al., 2012b) requires companies to account costs over the assets' lifetime. This Appendix presents an extension to the EBSD model formulation introduced in Chapter 2 in order to address the new regulatory requirements.

In the new model formulation, the planning horizon (set *T*) is extended by a number *n* of years (set *FF*). The model makes investment decisions over set *T*. No supply-demand balance modelling occurs over set *FF*, but just a continuation of the capital and operating costs over the scheme's lifetime. The capital and operating expenditure for each option *i,j* are accounted as one unique cash flow that occurs at the first year of activation of the optional schemes (investment decisions are made over set *T* only). Since the operating costs ($sfix_{i,j}$) are per year, their present worth value ($fopex_{i,j}$) is calculated as below (see also section 1.3 of Chapter 1):

$$fopex_{i,j} = fix_{i,j} \frac{\left[\left(1+ic\right)^{ul_{i,j}} - 1\right]}{\left[ic \times \left(1+ic\right)^{ul_{i,j}}\right]} \quad \forall i,j \in CON \qquad \text{I. 1}$$

In the equation above, $ul_{i,j}$ is the lifetime of the optional assets (set *OPTSOU*), *ic* is the cost of capital, while *CON* is the connectivity matrix which defines the network topology. Variable operating costs are accounted annually, over both set *T* and set *FF*, as their value depend on the schemes' optimal annual extent of use. Variable operating costs over set *T* are calculated as in Chapter 2 (equations 2.14 and 2.15). Variable operating costs over set *FF* are calculated using equations I.2 to I.6 below.

If *tmax* is the last year of the planning horizon (set *T*) a new continuous variable $QQ_{i,j,ff,scen}$ is introduced for each scheme *i,j*. $QQ_{i,j,ff,scen}$ is equal to $Q_{i,j,t,scen}$ at year *tmax*:

$$QQ_{i,j,ff,scen} \geq \sum_{t \in (T-t)+ff=n} Q_{i,j,t,scen}\Big|_{t=tmax} \times \left(AL_{i,j,t} - AL_{i,j,t-1}\right)$$
$$\forall (i,j) \in CON,\ ff \in FF, scen \in SCEN \qquad \text{I. 2}$$

A new continuous variable is then introduced ($QQQ_{i,j,ff,scen}$). $QQQ_{i,j,ff,scen}$ is defined over set FF and is equal to $QQ_{i,j,ff,scen}$ between year $tmax$ (excluded) and the last year of the asset's lifetime (see equation I.3). In the equation below, set FFF is an 'alias' of *set FF*, i.e., it refers to different time indexes that belong to set FF.

$$\begin{aligned}&QQQ_{i,j,fff,scen}\Big|_{fff\in FF} \geq QQ_{i,j,ff,scen}\Big|_{ff\in FF}\\ &\forall (i,j)\in CON,\ ff \geq fff, scen\in SCEN\end{aligned} \tag{I. 3}$$

Equation I.2 is not linear. In order to keep the model stated as a mixed integer linear program, a new continuous variable $QL_{i,j,t,scen}$ is introduced:

$$\begin{aligned}&Q_{i,j,t,scen}\Big|_{t=tmax} - m\left[1-\left(AL_{i,j,t} - AL_{i,j,t-1}\right)\right] \leq QL_{i,j,t,scen}\\ &\forall (i,j)\in CON, t\in T,\ scen\in SCEN\end{aligned} \tag{I. 4}$$

In the equation above, m is a scalar, i.e., the upper bound value for $Q_{i,j,t,scen}$. If asset i,j is not selected at year t ($AL_{i,j,t}$ $-AL_{i,j,t-1}$)=0, then equation I.4 becomes $QL_{i,j,t,scen} \geq (Q_{i,j,t,scen}|_{t=tmax} - m)$. Since the model is minimising costs and $Q_{i,j,t,scen}$ is a positive variable then $QL_{i,j,t,scen}=0$. If asset i,j is selected at year t, ($AL_{i,j,t}$ $-AL_{i,j,t-1}$)=1 and equation I.4 becomes $QL_{i,j,t,scen} \geq Q_{i,j,t,scen}|_{t=tmax}$. Since costs are minimised $QL_{i,j,t,scen}=Q_{i,j,t,scen}|_{t=tmax}$. Equation I.5 is obtained by replacing $QL_{i,j,t,scen}$ in equation I. 2:

$$\begin{aligned}&QQ_{i,j,ff,scen} \geq \sum_{t\in(T-t)+ff=n} QL_{i,j,t,scen}\\ &\forall (i,j)\in CON,\ ff\in FF, scen\in SCEN\end{aligned} \tag{I. 5}$$

Equations I.3, I.4, and I.5 are the model constraints. The weighted variable costs are over set FF are calculated in equation I.6:

$$vopexff_{i,j,t} = \frac{\sum_{scen} t_{scen} * var_{i,j} * QQQ_{i,j,t,scen}}{\sum_{scen} t_{scen}} \tag{I. 6}$$

If f' is the objective function equation in Chapter 2 (see equation 2.1), the new objective function f becomes:

$$min\ f = f' + \sum_{t=1}^{tmax} \frac{\sum_{i,j} capex_{i,j} + fopex_{i,j}\left(AL_{i,j,t} - AL_{i,j,t-1}\right)}{(1+d_r)^{t-1}} + \sum_{ff=1}^{N} \frac{vopexff_{i,j,t}}{(1+d_r)^{ff+T}} \qquad \text{I. 7}$$

In equation I.7 term ($AL_{i,j,t}$ - $AL_{i,j,t-1}$) identifies the first year of activation of selected schemes *i,j*. Figure 46 shows the calculation of capital and operating costs over time set *T* and set *FF*, if an asset lifetime of 80 years is considered.

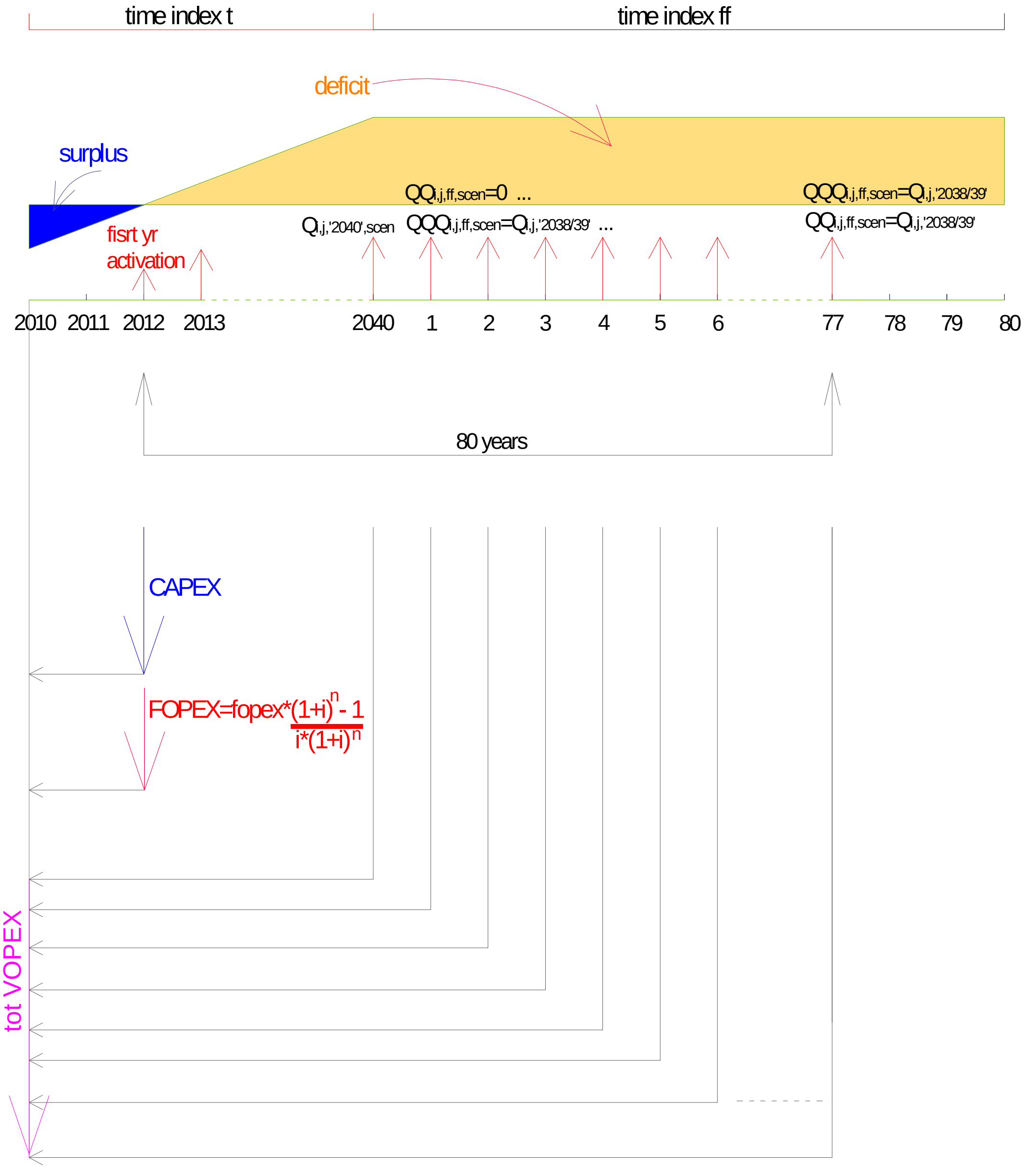

Figure 46: procedure to discount assets' annual costs over 80 years.

Appendix II - Generating near- optimal solutions

Least-cost optimisation can be used by water utilities to build long-term annual plans of new supply and demand management schemes. However it is likely that solutions that are near least-cost but have other benefits will be preferred by decision-makers. The study presented here argues for using a ‘modelling to generate alternatives’ (MGA) approach in supply-demand planning. MGA identifies a set of nearly optimal solutions with different decision variables. In England water planners use least-cost supply-demand optimised planning to defend their plans to regulators. MGA is applied to South East England, for the same network presented in Chapter 3 (see Figure 23), where £2.65 billion (Critchley and Marshallsay, 2013) are to be invested by private utilities over a 25 to 30 year planning horizon. 240 near-optimal solutions are examined within 10% of the optimum and 30 within 5%. The near-optimal plans are diverse; for example the optimal capacity of reservoir schemes and imports vary as much as 520% and 415% respectively. This diversity amongst the nearly least-cost plans suggests that, for the case-study system and others like it, other factors should be considered in addition to the economic cost, when designing portfolios of new supplies and demand management measures. The set of solutions generated using MGA are displayed in parallel axis plots in order to display the diversity in the frequency of scheme selection, extent of use over the planning horizon, and timing of asset activation. It is argued that exploring a diverse set of nearly optimal solutions is more appropriate than only considering the single least-cost solution or even the optimum under a few scenarios.

This Appendix is structured as follows: section II.1 introduces the literature review. Sections II.2 and II.3 describe the ‘modelling to generate alternatives’ approach and its application to the case study. Section II.3 presents the model results and is followed by discussion and conclusions in sections II.5 and II.6 respectively.

II.1 Literature review and context

Water planners usually use least-cost optimisation to ensure they cost-effectively expand their supply-demand systems. The ‘optimal’ solution helps water decision makers and regulators to coalesce around one plan amongst the many available ones. However, when applied to real-world planning problems, optimisation techniques can be limited due to complexities such as non-linearity and discontinuity present in the system (Zechman and Ranjithan, 2007) or due to the presence of knowledge, such as preferences of decision-makers, difficult to monetise and incorporate into the model.

This can translate into vague constraints and objectives and make the optimisation model ill-posed (Liebman C. J., 1976).

This issue gets amplified for large-scale problems where the introduction of an increased number of variables and uncertain factors multiplies the possibility for errors in the model structure and results (Harrington Joseph J and Gidley James S, 1985). Lee (1973) made a list of the main limitations of optimisation models for large-scale systems and analysed the planning context in which these have failed rather than evolved. Hobbs and Hepenstal (1989) applied Monte Carlo simulation to water resources problems and showed, for the case study, that the estimated solution (benefit) of the optimisation model can overstate the system's true performance.

Large scale problems may also present many alternative solutions with the same value of the objective function in the optimal solution, or that lie in the vicinity of the optimal solution (Rogers and Fiering, 1986). This phenomenon was examined by (Hopkins et al., 1982, Chang et al., 1982, O'Laoghaire T. D. and D., 1974) for a variety of water resource planning problems. Harrington and Gidley (1985) also found, for a water resource planning problem, many solutions whose value was within a few percent (1 to 5 %) of the global optimum.

Since a complex real word planning problem cannot be fully represented by an optimisation model, the 'optimal' solution does not necessarily coincide with the 'best' solution for the problem (Chang et al., 1982, Liebman C. J., 1976). The 'best' solution most likely lies in the inferior region in the objective space if there are one or more un-modelled objectives (Brill et al., 1990). Optimisation models can therefore be most valuable when used as a tool to generate alternatives for evaluation, allowing other criteria not included in the model to be considered in the decision making process (Chang et al., 1992, Brill, 1979b, Hopkins et al., 1982). This can provide a deeper understanding of the problem itself and help planners and decision makers in their final decision (Yeomans and Huang, 2003).

Alternatives can be generated through methods designed to produce solutions significantly different from previously designed solutions, as proposed in a series of papers authored or co-authored by E. D. Brill and S. J. Chang (Brill, 1979b, Brill et al., 1982, Brill et al., 1990, Chang et al., 1982, Chang et al., 1983, Hopkins et al., 1982, Chang and Liaw, 1984, Kshirsagar and Brill, 1984). This approach, called as 'modelling to generate alternatives' (MGA) is based on the hypothesis that alternative solutions perform better when the degree of difference among them higher. The argument for this is that, in order to include knowledge that cannot be embedded into the model, the decision maker has to consider a small set of alternatives that are perceived as different as possible compared to the problem optimal solution (Hopkins et al., 1982). Practice also dictates that good alternative solutions should not be more than 10% worse of the initial optimal solution to the problem (Yeomans and Huang, 2003). MGA techniques have been widely applied to water resource system planning problems and examples can be found in Hopkins et al. (1982), Uber et al. (1992) and Zechman and Ranjithan (2007).

II.2 Modelling to Generate Alternatives

A formal definition of MGA is provided by Brill (1979a) and is presented below. The first step consists of running the model presented in Chapter 2 and finding an optimal solution referred to as SOL. In the second step (step 2) the objective function equation 2.1 is replaced by equation II.1. Then, equation II.2 is introduced as model constraint. All other model constraints in Chapter 2 also included.

$$minimise \quad r = \sum_{t} \sum_{(i,j)\in K} AL_{i,j,t} \qquad \forall (i,j) \in CON, t \in T \tag{II. 1}$$

$$f' \leq T^* \tag{II. 2}$$

In the equation above, K is the set of all non-zero binary variables $AL_{i,j,t}$ in solution SOL, while f is used to denote the objective function equation of the original optimisation model (equation 2.1). T^* is an upper bound which sets the maximum amount by which target costs can deviate compared to costs in the original model solution SOL. If this model is run, it returns a new solution (schedule of scheme activation) which is referred to as SOL1. The third step consists of repeating step 2 where that the non-zero variables in the objective function II.1 (set K) includes all the non-zero variables in previous solutions (solution SOL and SOL1). This procedure is repeated many times until when a user-defined number of alternative solutions is obtained.

II.3 The MGA implementation

For this case study, the CPLEX *solution-pool* feature was used within GAMS. The *solution-pool* feature implements an extension of a branch and cut algorithm that allows to generates multiple nearly-optimal solutions. The user can adjust the number of solutions within the near-optimum solution pool by selecting how close, in percentage, the objective function values in the near-optimal solution must be to the optimal solution, given the capacity expansion model presented in Chapter 2. The user can also control the level of difference among the alternative solutions using a 'diversity' filter.

This analysis was applied to the WRSE network in Figure 23 and does not use confidential cost dataset used in other efforts (Padula et al., 2013, P. H. von Lany, 2012, R. Critchley and D. Marshallsay, 2013). The WRSE network used here has different input data than those presented in Chapter 3: scheme costs (extrapolated from the net present value figures in water company plans) were later improved returning the network in Figure 23.

II.4 Model results

II.4.1 The optimal solution

The total net present cost of the solution is £ 1.09 billion; the optimal programme (annual schedule of options and extent of use) is dominated by investments on imports TR from areas outside the network. TR schemes provide a total of 1,217 10^3 Ml/d equivalent to the 30% of the total water supplied. The second highest volume is from metering (MET) schemes (1,113 10^3 Ml/d, which corresponds to the 27.6% of the total supply). Table 50 shows the total extent of use (in 10^3 Ml/d and in %) and the total discounted costs (capital expenditure, fixed and variable operating costs) for selected schemes aggregated by type. Scheme types are listed in Chapter 2.

	Total water supplied [10^3 Ml/d]	Percent of network's total water supply	Capital [10^3 £]	Fixed operating [10^3 £]	Weighted variable operating [10^3 £]
MET	1,113	28%	377	6	0.3
TR	1,217	30%	568	19	6
RES	181	4.5%	202	77	0.8
DESAL	402	10%	230	3	0.2
GW	293	7%	2156	7	0.3
LEAK	265	7%	16	196	8
ASR	213	5%	150	1.4	0.06
ER	58	1%	162	15	0.6
NI	116	3%	43	349	0.01
WEFF	82	2%	53	1	0.01
SW	73	2%	84	3	0.1
WTW	21	0.5%	17	2	0.06

Table 50: Total extent of use in [10^3 Ml/d] and discounted costs in [10^3 £] for the least economic cost solution. Numbers may not add up due to rounding.

Table 50 shows that the plan's impact would be substantial; nearly a third of water coming from inter-regional transfers would lead to a large carbon footprint from energy use and a high environmental footprint. The second largest water volume comes from metering options which are typically regarded in the sector as uncertain and regionally variable. For various strategic, political and environmental reasons it is reasonable that before implementing this plan, planners would investigate other portfolios of options of similar cost but with different mixes of new supply and demand management schemes.

II.4.2 Near-optimal results

A set of solutions within 10% of the least-cost supply-demand plan is generated. The margin of error on the model input data reaches or surpasses 10% in many cases and so it is reasonable to consider plans within 10% of the least-cost solution (Yeomans and Huang, 2003).

The CPLEX *diversity filter* feature is used to obtain solutions as diverse as possible from each other. This resulted in 240 near-optimal solutions. Figure 47 shows the near-optimal solutions (darker grey lines indicate proximity to optimal solution) and the least-cost solution (dotted red line) in a parallel coordinate plot (Meeks L. and Rosenberg D.). The darker the grey line, the closer are (in cost) the near-optimal solutions to the least-cost plan (dashed red line).

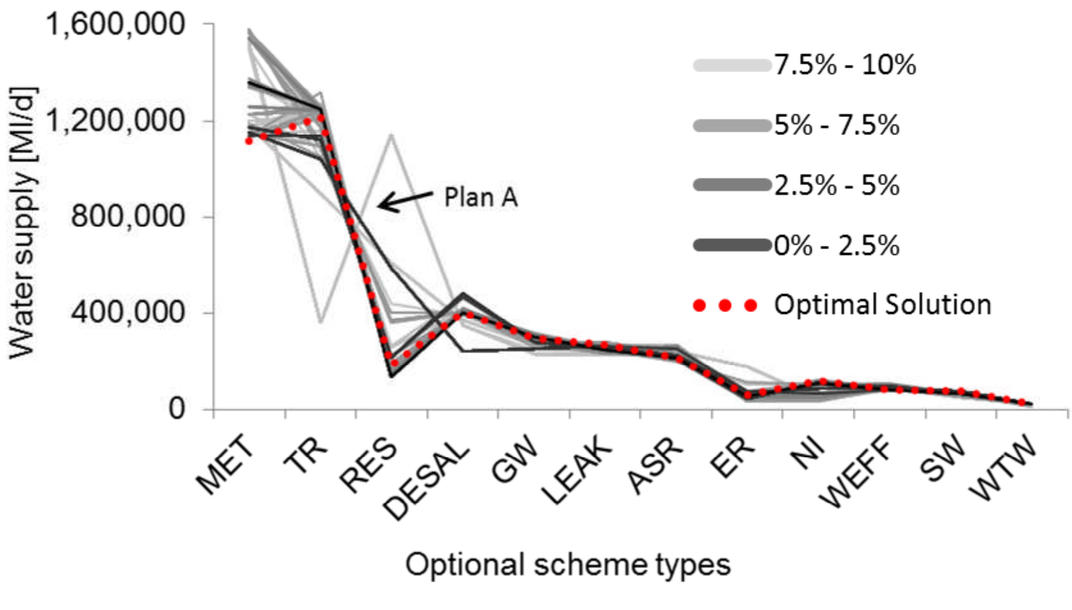

Figure 47: Total water supply over the whole planning horizon from supply-side and demand management options grouped by type over the 240 near-optimal solutions within 10% of the least-cost plan.

Graphing the 240 solutions on a parallel axis plot (Figure 47) shows the diversity of the near-optimal plans across the different scheme types. Over all the 240 near-optimal solutions it is possible to find near-optimal plans whose cost is within a few percent of the least-cost plan, and that present a high diversity of scheme selection and extent of use. For example portfolio ‘A’ in Figure 47 is only 6% more expensive than in the least-cost solution, but has a 30% lower extent of use of TR imports (imports decrease from Ml/d 1217×10^3 in the least-cost plan to Ml/d 356×10^3 billion in plan ‘A’), and a 24% higher extent of use of reservoir RES schemes (supply from RES schemes increases from 181×10^3 Ml/d in the least-cost plan to Ml/d 757×10^3 Ml/d in plan ‘A’).

Using the *solution pool* CPLEX feature, 30 near-optimal solutions are found within 2.5% of the optimal plan (see Figure 48). The number of solutions presented in Figure 48 is small enough that decision-makers can more easily consider each individual alternative plan and its un-modelled advantages and disadvantages.

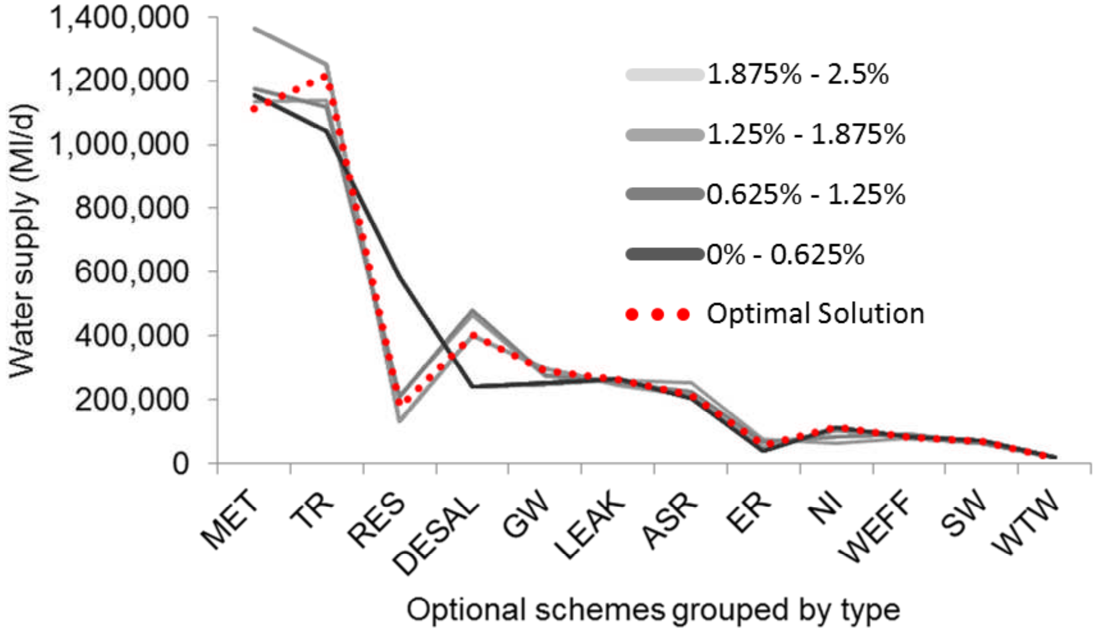

Figure 48: Total water supply over the planning horizon from supply-side and demand management options grouped by type over the 30 near-optimal solutions within 2.5% of the least-cost plan.

II.4.2.1 Analysis of reservoir schemes

Parallel axis plots can also be used to show results for individual schemes that are selected over the near-optimal plans. We show this for reservoir (RES) options and TR imports (section *II.4.2.2*), which are the one that vary mostly over the near-optimal solutions.

Figure 49 shows the RES schemes that are selected over the 240 near-optimal solutions within 10% of the least-cost plan. The darker the grey line, the closer are (in cost) the near-optimal solutions to the least-cost plan (dashed red line). Ordering from left to right is made by frequency of selection (higher frequency on the left, lower frequency on the right). This ordering is useful to identify which scheme selections are likely low-regret decisions. For example reservoir schemes *P064*, *P014*, *P021* and *HV* are selected in each of the 240 near-optimal solutions, while scheme *P065* is selected in just three near-optimal solutions.

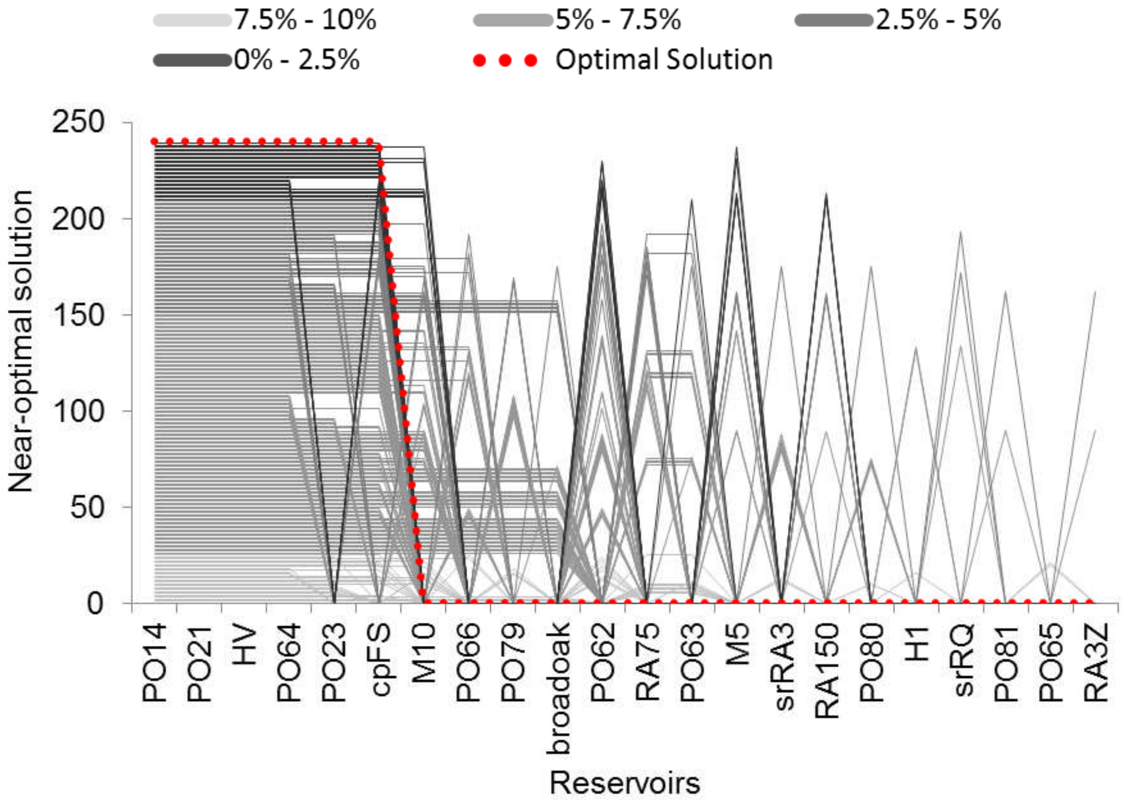

Figure 49: Diversity in the frequency of RES selection amongst the 240 near-optimal solutions within 10% of the optimum. Each line represents one of the 240 solutions.

Figure 50 displays the percentage level of utilisation (options optimal yield divided by their maximum capacity) of selected reservoir options, over the near-optional solutions. In Figure 50, the reservoir schemes on the left have a higher extent of use than those listed on the right.

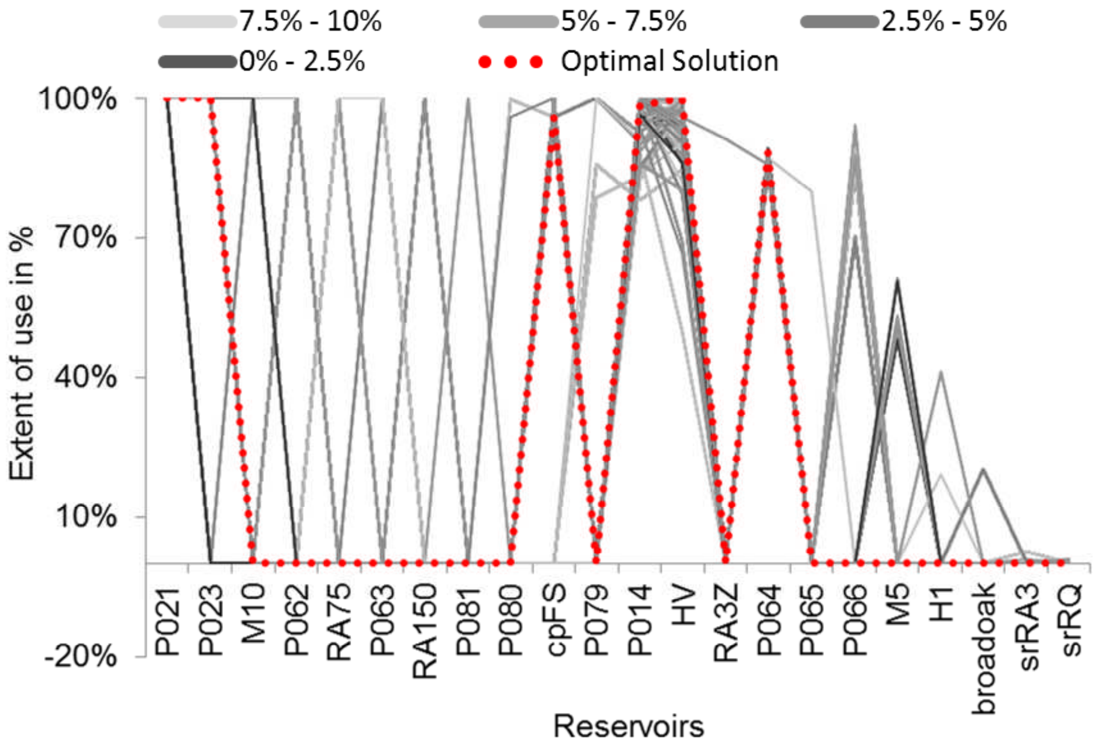

Figure 50: Extent of use, in percentage, of reservoir schemes selected over amongst the 240 near-optimal solutions within 10% of the optimum. As the objective function value (cost) in the near-optimal plans decreases the solution colour darkens.

Figure 50 shows that the extent of use of asset *HV* varies between 50% and 100%. RES option *P021* instead is used at 100% of its capacity over all of the 240 near-optimal solutions. This indicates that building this asset is a cost-effective decision. RES scheme *M5* has a maximal usage of just 61% which indicates that this option is likely over-sized.

Figure 51 shows the year of activation of reservoirs schemes over the planning horizon (y-axis). Reservoirs along the x-axis are arranged by order by year of activation (schemes on the left are activated earlier than those on the right). The analysis of Figure 49 showed that reservoir schemes *P064*, *P014*, *P021* and *HV* are likely low-regret decisions (these schemes are selected over all the 240 near-optimal plans), while Figure 51 shows that there is some diversity among the near-optimal solutions regarding the year in which these schemes are selected.

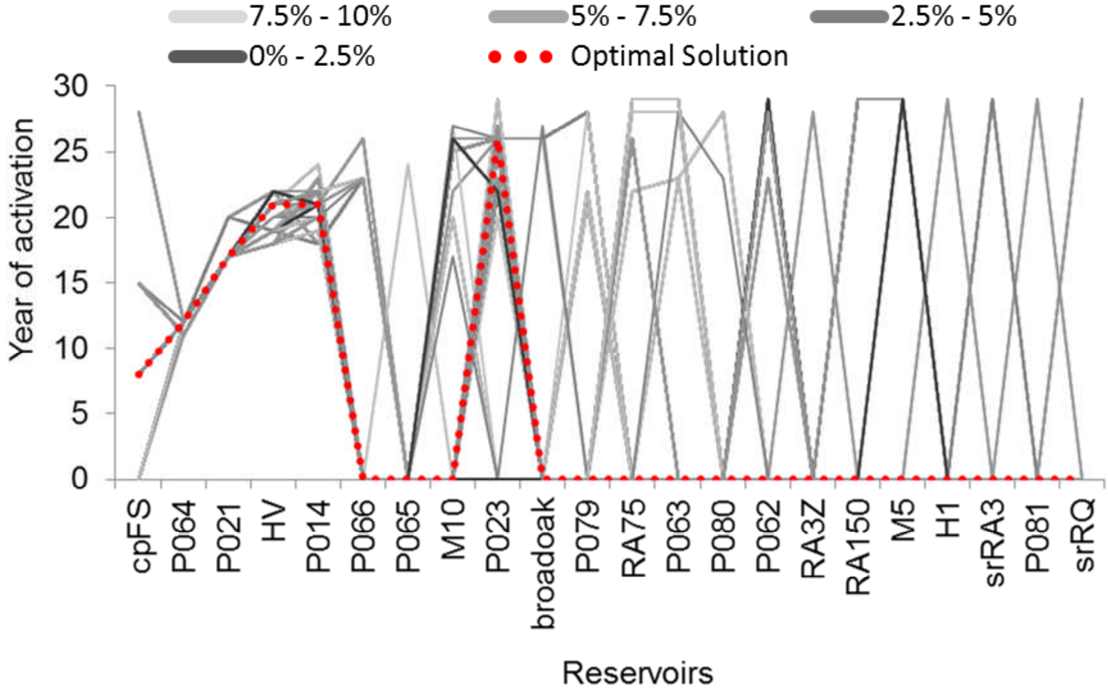

Figure 51: Diversity in year of activation, for reservoir schemes selected over the 240 near-optimal solutions within 10% of the optimum. As the objective function value (cost) in the near-optimal plans decreases the solution colour darkens.

II.4.2.2 Analysis of transfer schemes

An examination of selected imports (TR) within the near-optimal solutions reveals diversity in the selection, timing and usage. Figure 52 is a parallel axis plot like the one in Figure 49: for each of the 240 near-optimal solutions, a line is drawn that shows the composition (schemes types) of all 240 portfolios in one plot.

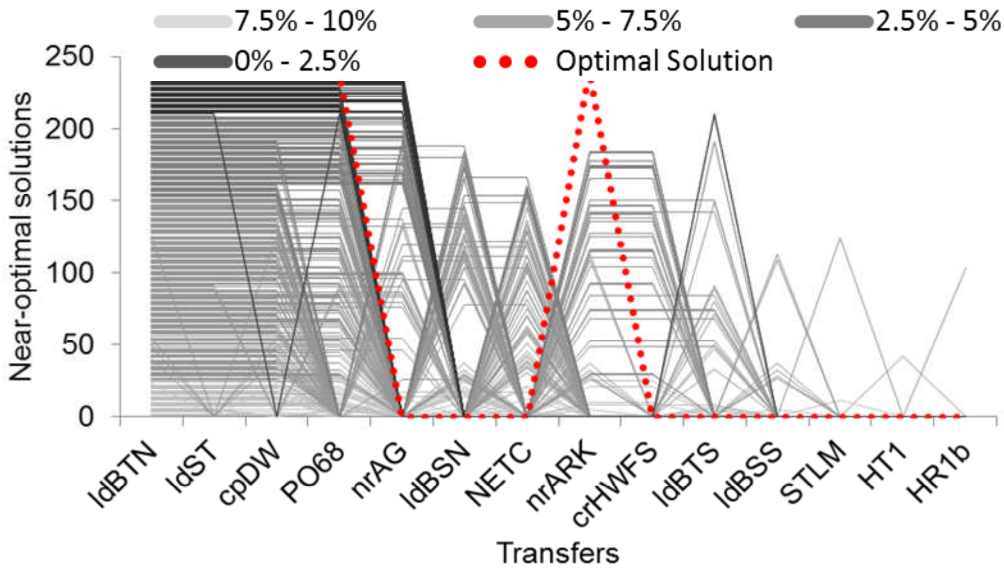

Figure 52: Diversity in the frequency of transfer scheme selection amongst the 240 near-optimal solutions within 10% of the optimum. Each line represents one of the 240 solutions. As the objective function value (cost) in the near-optimal plans decreases the solution colour darkens.

The transfers along the horizontal axis are ranked by frequency of selection (the most selected transfers are on the left, the lower selected one on the right). Among the 240 near-optimal solutions within 10% of the global optimal solution, only 46 near-optimal plans include the asset *nrARK* which is selected in the least-cost plan. Scheme *nrARK* is also not selected in any of the 30 near-optimal solutions within 2.5% of the least-cost plan. This suggests that the implementation of this asset could be avoided if it presents any special technical risk or political challenge.

Figure 53 shows the percentage level of utilisation of selected transfer options (options optimal yield divided by their maximum capacity) over all near-optional solutions. By comparing Figure 53 with Figure 50, it appears that there is more diversity in the usage for transfer schemes than for reservoirs. The extent of use of some transfer schemes, vary considerably over the near-optimal schemes. For example, transfers *P068* is used between 21% and 88% of its capacity over the near-optimal solution.

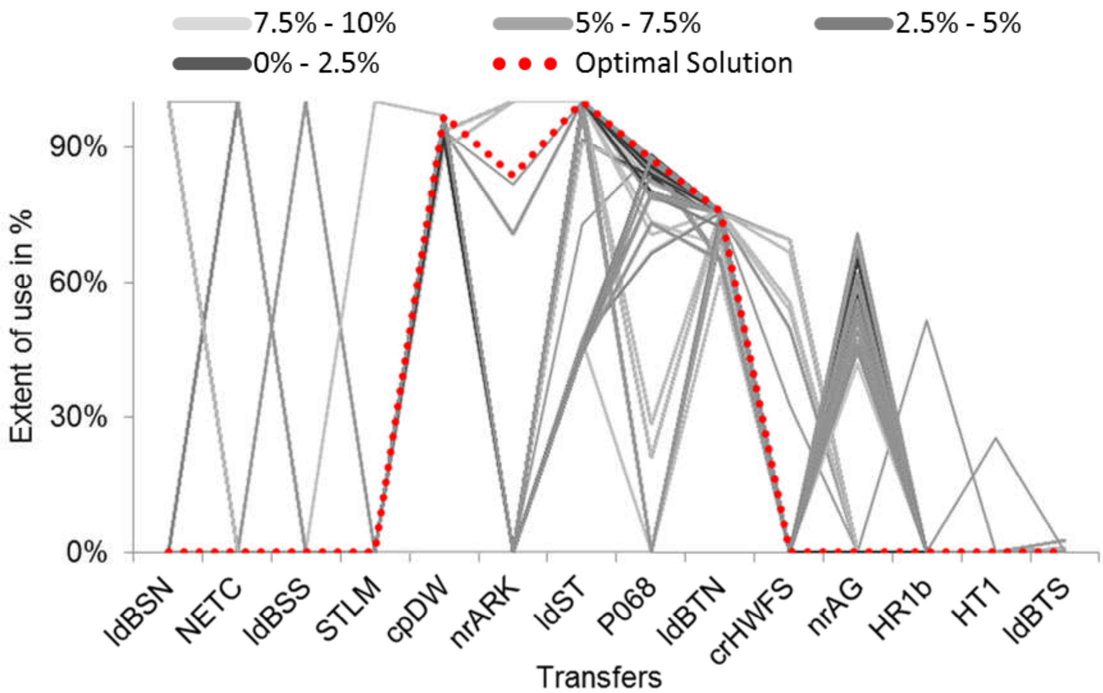

Figure 53: Percentage of maximum extent of use over the planning horizon for each transfer node over the 240 near-optimal solutions within 10% of the optimum. Each line represents one of the 240 solutions. As the objective function value (cost) in the near-optimal plans decreases the solution colour darkens.

Figure 54 shows that there is also variability among near-optimal plans in the year which the transfers are activated. Such a plot could be used by the decision-maker to investigate whether the year of implementation of some problematic investments could be delayed over the planning horizon.

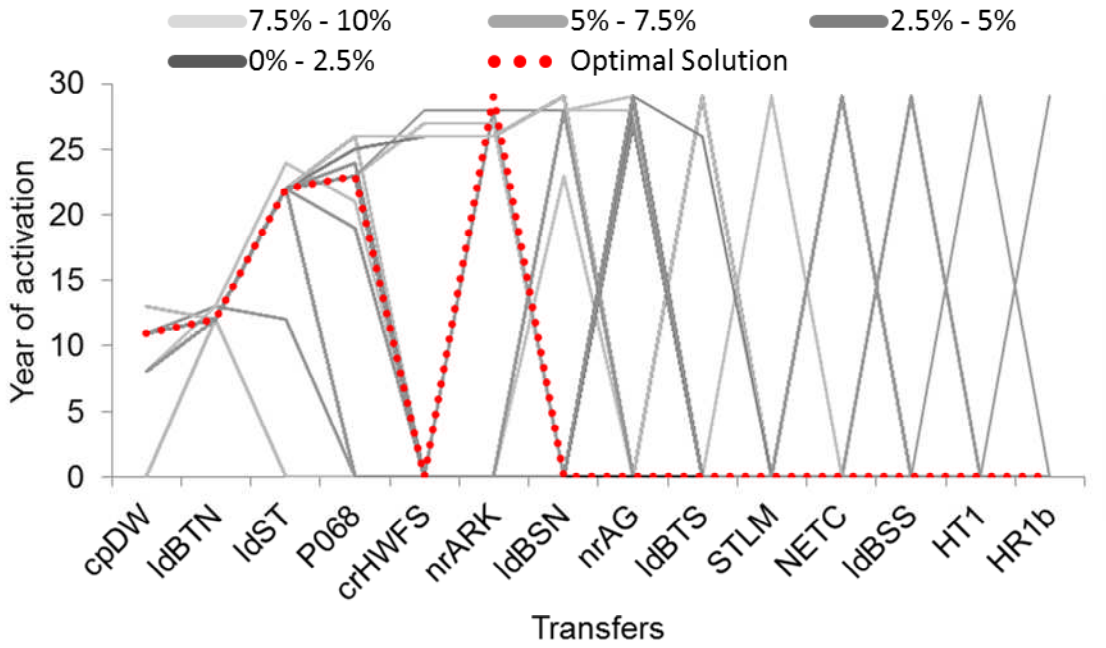

Figure 54: Diversity in year of activation, for transfer schemes selected over the 240 near-optimal solutions within 10% of the optimum. Each year of the 29 year planning horizon is represented on the y-axis. As the objective function value (cost) in the near-optimal plans decreases the solution colour darkens.

II.5 Discussion

In this Appendix, an optimisation technique called 'modelling to generate alternatives' is applied to a water supply capacity expansion planning problem. This allows generating 240 near-optimal solutions within a 10% (in cost) of the least-cost plan, and 30 near-optimal solutions within a 2.5% of the least-cost plan. Parallel axis plots are used to show the diversity of the near-optimal set of interventions with regards to extent of use (least-cost quantity) of selected asset types (Figure 47 and Figure 48) or specific assets (Figure 50, Figure 53), in the frequency of activation of specific assets (Figure 49 and Figure 52), and with regard to the timing of activation for selected schemes (Figure 51, Figure 54). The contribution of the information provided by the parallel axis plots and the policy significance of this work is reflected below.

II.5.1 Content and use of near-optimal parallel axis plots

Figure 47 and Figure 48 show the total capacity expansion (in Ml/d) for each scheme type across the near-optimal solutions within the 10% and 2.5% of the least-cost plan respectively. If planners consider certain asset types being less reliable or less politically or socially beneficial, these results show the potential for planners to limit the use of schemes from one or more types.

Figure 50 and Figure 53 show the frequency of selection of specific optional assets (reservoirs or transfers) over the 240 near-optimal plans within 10% of the least-cost solution. These graphs allow planners to visualise how frequently certain investments are part of a near-optimal mix and can help planners to choose plans that include or exclude particular schemes. Assuming that the modelling to generate alternatives algorithm has enforced diversity in the near-optimal solutions, the fact that a particular asset appears in most solutions indicates that it is more likely to be appropriate under a wide range of designs and can be considered a low-regret investment.

Figure 49 and Figure 52 show the diversity of the near-optimal solutions with regards to the maximum level of utilisation (in percentage) of selected reservoirs and transfers. These plots help planners to quickly assess which schemes are used intensively and therefore what are the most cost-effective schemes to operate.

Finally, Figure 51 and Figure 54 show the diversity of the first year of activation of selected schemes over the planning horizon. These plots allow planners to understand how urgent some schemes are to enable a cost-effective expansion, or to potentially delay the implementation of controversial schemes. For example, options *RA75*, *RA150* and *RA3z* represent four possible implementations of the Upper Thames reservoir (UTR) in the Thames Company area. UTR can be built with a maximum capacity of 75 Mm^3 (*RA75*) or with a maximum capacity of 150 Mm^3 (*RA150*). In the latter case the UTR can serve three water recourse zones (option *RA3z*) or only two (option RA150). Options *RA75*, *RA150* and *RA3z* are mutually exclusive. The UTR scheme is perceived to be controversial with groups trying to block its implementation due to local landscape and heritage issues. Therefore if the planner decides to build the UTR, than he can opt for adopting one of the near-optimal solutions (see Figure 51) which allow delaying its implementation over the planning horizon.

The parallel axis plots represent an initial exploration of the near-optimal solution set. Further analysis would involve tracking promising schemes and identifying ranges considered desirable for whatever reason (e.g. ‘solutions with at least 20% increase in leakage reduction are considered desirable from a policy perspective). Especially if the near-optimal set if large, this work could be tedious and specialty software would likely be helpful, e.g. software that would allow filtering the parallel axis plot by conditions and labelling. AeroVis[1] can be used for this scope. AeroVis is a visual platform that

[1] https://www.decisionvis.com/products/aerovis/

enables ‘brushing’ solutions to display only those that fit specific criteria defined by the user.

II.5.2 Policy implications and conclusive remarks

The policy implications of the South East England regional water supply system planning case-study are significant. This work shows that allowing a 2.5% or 10% economic deviation away from the least-cost plan leads to substantially different plans. For example plan ‘A’ showed in Figure 47 shows a very different mix of schemes (more reliant reservoir options rather than on imports from zones external to the network) and is only within 6% of the least-cost design.

This exercise reveals that only reporting the least-cost schedule of supply upgrades and water demand management schemes, gives an incomplete picture of the options available to both regulators and company decision-makers. Considering near-optimal plans drastically increases the freedom of planners to consider un-modelled factors and other strategic priorities and would allow them to recommend more appropriate and beneficial mixes of new supply and demand management options.

II.6 Conclusion

The modelling to generate alternatives application presented in this Appendix included the detailed analysis of near-optimal solutions within a 10% distance of the least-cost solution. The set of near-optimal solutions are displayed in parallel axis plots in order to show the diversity in the frequency of scheme selection, extent of use over the planning horizon, and timing of asset activation. These plots show that the near-optimal set of alternative plans presents significant levels of diversity. For example, a plan with a 24% greater usage of reservoirs and 30% lower usage of imports is only 6% more expensive than the least-cost solution plan. Also, certain plans including controversial assets were nearly the same cost as other plans without them.

The case study provides a basis to argue that exploring a diverse set of nearly optimal solutions is more appropriate than only considering the single least-cost solution or even the optimum under a few scenarios. This diversity amongst nearly least-cost plans suggests that, for the case-study system studied and others like it, other factors should be considered in addition to economic cost when designing portfolios of new supplies and demand management measures.

Ideally England will transition to a multi-criteria planning framework where other objectives can be quantified and used to assess options. The current work shows considering non-monetary criteria is needed because the different plans are insufficiently distinguishable by economic criteria alone and therefore systematic adoption of the least-cost solution is to some extent arbitrary and unlikely conducive to the socially optimal plans. This inability of economic criteria alone to justifiably select a preferred plan points to a larger question: whether economic cost-benefit analysis alone is sufficient to justify large investments of public funds in complex infrastructure systems such as regional water supply where each plan involves a mix of monetisable and non-monetisable consequences.

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