MODEL SUMMARY

The DMF Model is a decision support tool that selects, from a range of potential investment options, combinations of those options that satisfy demand scenarios for the delivery of water to customers over a specified planning period. The basis of the portfolio selection method contained in the DMF Model is that of the Economics of Balancing Supply and Demand (EBSD) framework[1]. In line with more recent UKWIR guidance, this has been extended to allow investment option performance against other objectives to be assessed and incorporated into the portfolio selection process using Multi-Criteria Analysis (MCA) techniques[2]. Water Quality requirements are also incorporated into the selection process.

For example, the DMF model can calculate:

- The selection of options (the portfolio) that meets the demand scenarios at least (discounted) cost
- The portfolio of options that maximises performance against other single objectives (e.g. operational resilience, environmental sustainability, deliverability, etc.) while still meeting the demand scenarios.

In practice, determining the portfolio that best meets business needs is rarely so straightforward. Trade-offs must be made against all the objectives of interest (including cost). To this end more complicated scenarios can be considered in the DMF model, for example:

- Determine the least cost portfolio that provides minimum specified levels of operational resilience and deliverability
- Determine the least cost portfolio that does not exceed maximum levels of capital expenditure within specific time periods.

The DMF model allows decision makers to investigate optimisation scenarios of this type. Its purpose is to provide information to enable them to formulate the best investment/operational strategy for the business and its customers and to meet the requirements of regulatory authorities.

The scope of the DMF Model was chosen after performing a problem characterisation assessment that identified that an extended approach to modelling (i.e. in addition to meeting EBSD requirements) was merited.

MODEL STRUCTURE

The high-level model structure is defined in Figure 1.

- Data defining the various capital investment, operational and demand management options are imported into a central database from Excel workbooks
- This data is processed to:
    - Create a profile of annual costs over the (80-year) period that includes capital investment and renewals, both fixed and variable operational costs, system benefits and financing costs
    - Filter out those potential investment options that cannot deliver against the required water quality criteria
- Discount rates are applied to calculate discounted costs for each option in each year and weights are applied to objective criteria to determine scores for objectives in each year
- The type of optimisation to be performed (minimise cost or maximise against objective), the demand scenarios (DYAA, NYAA and DYCP) that must be met and with any other constraints that must be satisfied by the selected portfolio are specified in an optimisation scenario
- All of this data is used to formulate the portfolio selection problem as a mixed integer programming (MIP) problem, which is solved using the DMF Optimisation Engine
- A reporting module enables:

---

[1] UKWIR, 2002, The Economics of Balancing Supply & demand (EBSD): Guidelines
[2] UKWIR Report Ref. No 16/WR/02/10, 2016, WRMP 2019 Methods – Decision Making Process: Guidance

- o The detailed characteristics of individual portfolios to be analysed (e.g. content, costs, yield, multi-criteria scores)
- o The performance of different portfolios to be compared
- o The generation of Parallel Coordinate Plots and multi-criteria comparison plots.
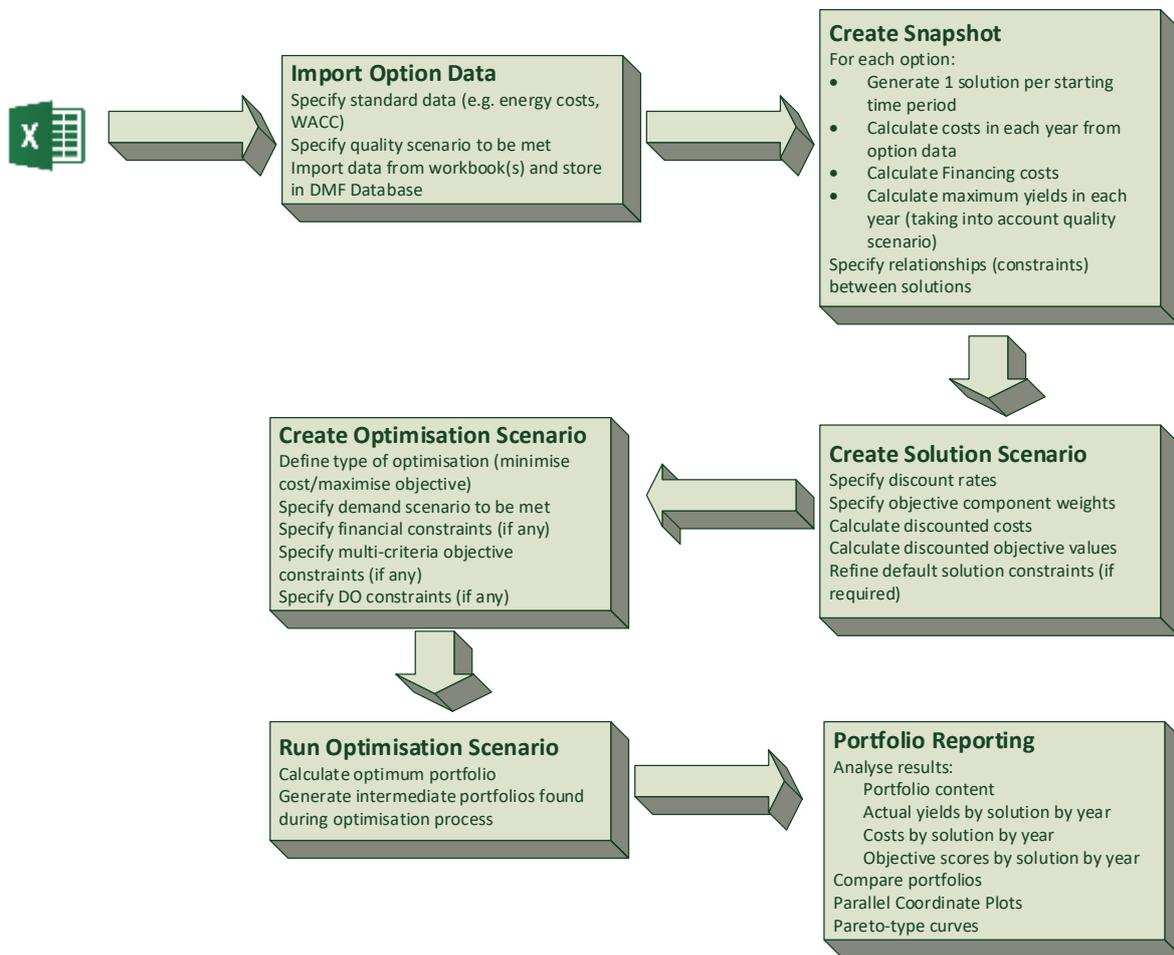
Import Option Data
Specify standard data (e.g. energy costs, WACC)
Specify quality scenario to be met
Import data from workbook(s) and store in DMF Database

Create Snapshot
For each option:
- Generate 1 solution per starting time period
- Calculate costs in each year from option data
- Calculate Financing costs
- Calculate maximum yields in each year (taking into account quality scenario)
Specify relationships (constraints) between solutions

Create Optimisation Scenario
Define type of optimisation (minimise cost/maximise objective)
Specify demand scenario to be met
Specify financial constraints (if any)
Specify multi-criteria objective constraints (if any)
Specify DO constraints (if any)

Create Solution Scenario
Specify discount rates
Specify objective component weights
Calculate discounted costs
Calculate discounted objective values
Refine default solution constraints (if required)

Run Optimisation Scenario
Calculate optimum portfolio
Generate intermediate portfolios found during optimisation process

Portfolio Reporting
Analyse results:
  Portfolio content
  Actual yields by solution by year
  Costs by solution by year
  Objective scores by solution by year
Compare portfolios
Parallel Coordinate Plots
Pareto-type curves

Figure 1 – Model Structure

DMF MODEL TERMINOLOGY

The following basic terminology will be used below when defining the optimisation model.

Option	A potential investment option, for which data is imported from the workbooks, that could contribute to meeting the demand scenario.
Solution	Each option can be selected to start in several alternative years. A solution is an option selected to start in an individual year. One option can generate many solutions. Solutions provide the model with the ability to schedule investments in the best way.
Portfolio	The collection of solutions that are funded over the planning period under consideration
Optimum Portfolio	The portfolio of solutions that best meets the portfolio objective (e.g. minimise NPC, maximise resilience, etc.) subject to any constraints that have been set.
Selected	A solution is selected when it has been included in the optimum portfolio (Capex and financing costs have started to be spent).

Active	A solution is available to give output but is not necessarily being utilised. The life cycle (renewal) costs, financing costs and the fixed opex are being spent. An option is not active if it has been selected but is still under construction.
Inactive	An existing solution may become inactive, for example, when another option replaces it. For example, a base Seedy Mill capital maintenance option becomes inactive once one of the upgrade options becomes active. Lifecycle and fixed Opex costs stop being spent. Once something has become inactive it cannot become active again.
Utilised	A solution is being utilised in any year when it is contributing to meeting at least one element of the demand scenario.

SPECIFYING POTENTIAL INVESTMENT OPTIONS

OPTION COSTS AND BENEFITS (FINANCIAL)

Cost data for options is provided to the model so that it is able to comply with the requirements of the WRMP 19 Planning Tables Instructions[3]. Cost data is broken down as follows:

- Construction Phase Expenditure (Capital Investment)
- Lifecycle Expenditure (Capital Renewals). (In some cases, an 80 year profile of capital renewal costs is collected. In other cases, costs are specified with a frequency of renewal and the model calculates the 80-year capital renewal cost profile)
- Fixed operating costs
- Variable operating costs
    - Energy (entered in KwH/Ml which is converted to a cost in £/Ml)
    - Chemicals (£/Ml)
    - Other (£/Ml)

Social and Environmental costs are not considered directly in the model. In line with UKWIR Guidance[4] (page 30) the DMF model incorporates an assessment of non-monetised environmental and social impacts utilising its multi-criteria model.

YIELD/DEMAND REDUCTION DATA

The data for each potential option has either:

- Maximum values of deployable output for DYAA, NYAA and DYCP
- A 40-year demand reduction profile (that is extended to 80 years by assuming the reduction remains constant in the subsequent 40 years)

OPTION QUALITY DATA

The Water Available for Use (WAFU) from an option is modelled so that it may vary depending upon the quality requirements that are placed upon it. This approach is covered in detail in the 'Decision Making Framework for South Staffs Water' documentation[5].

Figure 2 shows an example of the type of data that is collected.

---

[3] Environment Agency, Water Resources Planning Tables – Instructions, Version 16, Revised May 2017
[4] UKWIR Report Ref. No 16/WR/02/10, 2016, WRMP 2019 Methods – Decision Making Process: Guidance
[5]

	1	2	3	4
E Coli	7	10	10	
Coliforms				
Clostridia				
Cryptosporidia				
Pesticides	5	5	7	
Nitrates	5	5	7	
THM formation potential	5	5	7	
Metaldehyde	5	5	5	
Fe	5	5	7	
Mn	5	5	7	
Al	5	5	7	
Volume	210	139	100	
Confidence	5	5	5	

Figure 2 – Example Option Quality Data

The left-hand column shows a number of quality categories (E-coli, Coliforms, Fe, etc.). Each of the columns provides a range of quality scores that can be met at a particular volume of output). In the example, the option can deliver 210Ml/d against a quality standard of (7,5,5,5,5,5,5,5), can deliver a volume of 139Ml/d against a quality standard of (10,5,5,5,5,5,5,5) and a volume of 100Ml/d against a quality standard of (10,7,7,7,5,7,7,7). It cannot meet a higher quality standard and so the volume of water available reduces to 0.

MULTI-CRITERIA OBJECTIVES

The DMF incorporates a Multi-Criteria Analysis approach to assessing benefits against various objectives in a non-monetised form. The details of the Multi-Criteria Analysis approach are contained in the 'Decision Making Framework for South Staffs Water' documentation[6]

The following multicriteria objectives are included in the DMF Model. Most are broken down into further objective components.

- Operational Resilience
  - Improvement in Reliability
  - Improvement in Flexibility
  - Improvement in Diversity of Supply
- Deliverability
  - Third Party Approvals
  - Benefits Proven
  - Operations Proven
  - Third Party Supply Chain
- Environmental Sustainability
  - Carbon Emissions
  - Biodiversity
  - Sustainable Abstraction
- Social Sustainability
  - Community Disruption
  - Community Wellbeing
  - Customer Water Use
- Customer Preference.

Individual components can be weighted to vary the final objective score in relation to the relative importance of the components.

When deciding upon the final portfolio of options to include in the WRMP/Business Plan the multi-criteria scores are used to highlight trade-offs between the different types of impacts.

---

[6]

Relationships With Other Options

The optimisation model must understand the relationships between the different options available for selection. Table 1 provides examples of the constraints used to specify these relationships.

Constraint Type	Example
Two or more options are mutually exclusive (i.e. only one of them can be selected into the portfolio)	Options to reduce leakage are presented as bundles of schemes that deliver varying levels of reduction. Each bundle increases the reduction by supplementing the schemes included in the previous bundle. Only one of the bundles can be selected into the portfolio otherwise double counting would occur.
Two or more options can be selected into the portfolio but must not be active at the same time	Seedy Mill Capital Maintenance option may be included initially but may be superseded by an upgrade/rebuild option that increases its capacity. Both options may be selected into the portfolio but cannot be active at the same time (they have the same water sources).
Option i can only be selected if Option j has been selected and is active in the year prior to selection	This constraint allows phasing dependencies between options to be specified. Phase 2 of a scheme may not be selected, for example, until Phase 1 is complete and actively delivering water.
Option i can only be selected if Option j has been selected and is active in the year construction of Option i completes	This constraint is like the previous constraint but allows for slightly different timing for the sequencing of the two options.
Option i cannot be selected after Option j has been selected	It may be possible, for instance, to increase capacity of a Treatment works to 50 Ml/d and then later to 60 Ml/d. This constraint allows such options to be entered but stops them being selected in the wrong order.
Option i can only be selected into the portfolio if one of Options j, k, l, …. has also been selected and remains active in the previous year	Some options may require one of a number of alternatives to be implemented before they can be selected themselves. This constraint enables this situation to be modelled. An increase in the capacity of Hampton Loade to 250 Ml/d is dependent, for example, on one of a number of network upgrades being implemented first.

Table 1 – Option Constraint Types and Examples

Standard Data

In addition to data for individual options, the DMF model requires:

- Energy costs rates over time
- A CO_2e factor to enable calculation of the amount of carbon generated because of energy usage
- The Weighted Average Cost of Capital (for use in generating financing costs)
- The number of days per year to use to apportion variable annual costs between DYAA, NYAA and DYCP.

The need for the latter requires some explanation. Ultimately, the total discounted costs of an option when selected into the portfolio will depend upon what proportions of its relevant DOs are used to meet the individual DYAA, NYAA and DYCP demand scenarios. Calculation of a representative overall cost of the solution requires that these cost components be weighted in a sensible fashion. If values of 320, 3, and 42 are entered, for example, then the relative weights for DYAA, NYAA and DYCP costs will be 320/365, 3/365 and 42/365.

Required Quality Scenario

The quality scenario defines the quality standards that must be met for each water source. It is defined by a series of quality profiles (one for each water source) of the form shown in Figure 3.

	Standards to achieve (1,3,5,7,10)															
	Next AMP					Following AMP					Future AMPs					
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 6	Year 8	Year 9	10	AMP	AMP	AMP	AMP	AMP	AMP
E Coli	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Coliforms																
Clostridia																
Cryptosporidia																
Pesticides	5	5	5	7	7	7	7	7	7	7	7	7	7	7	7	7
Nitrates	5	5	5	7	7	7	7	7	7	7	7	7	7	7	7	7
THM formation potential	5	5	5	7	7	7	7	7	7	7	7	7	7	7	7	7
Metaldehyde	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Fe	5	5	5	7	7	7	7	7	7	7	7	9	9	9	9	9
Mn																
Al																

Figure 3 – Required Quality Profile

The format of each column in a quality profile defines the minimum standard that must be met in that time period. Quality standards are provided in the columns for individual years of the first two AMPs and, subsequently, for individual AMPs.

GENERATION OF POSSIBLE INVESTMENT SOLUTIONS

BASIC PROCESSING FOR SOLUTIONS

The following basic processing is performed to generate potential investment solutions from the Option data:

- For each option one solution is generated for each potential start year (the start years of individual options can be limited in their input data. All capital maintenance options are specified to begin in 2020, for example, if they are to be included at all)
- The input cost data is processed to provide a breakdown of costs in each year for:
  - Capital Investment
  - Capital Renewals
  - Fixed Opex
  - Variable Opex DYAA – assuming use of full DYAA DO, but weighted as explained in the Standard Data section
  - Variable Opex NYAA – assuming use of full NYAA DO, but weighted as explained in the Standard Data section
  - Variable Opex DYCP – assuming use of full DYCP DO, but weighted as explained in the Standard Data section
- Objective Scores for each solution in each year are calculated using a set of weights for each objective component

APPLYING THE QUALITY SCENARIOS

The maximum yields (for DYAA, NYAA and DYCP) for an option are calculated by limiting its yield in any year as a result of the quality scenario in place for its water source and the option's quality data. Combining the quality data of Figure 2 with the quality scenario of Figure 3, for example, limits the yield available from the option as shown in Figure 4.

	Next AMP					Following AMP					Future AMPs					
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 6	Year 8	Year 9	Year 10	3rd AMP	4th AMP	5th AMP	6th AMP	7th AMP	8th AMP
Maximum Volume	139	139	139	100	100	100	100	100	100	100	100	0	0	0	0	0

Figure 4 – Volume available from Option after applying Quality Profile

FINANCING COSTS

In line with the Guidance document from EA[7] and its supplementary note[8] Financing Costs are calculated for each solution based on its cumulative capital investment. Only construction investment is considered when calculating the financing costs and it is

---

[7] Environment Agency, Water Resources Planning Tables – Instructions, Version 16, Revised May 2017
[8] Approach to discounting in the 2019 Water Resource Management Plans, Nick Haigh (Defra), Harry Walton (EA) and Peter Hetherington (Ofwat)

assumed that they will be incurred so long as the solution is active in the portfolio. In general, once a solution becomes inactive its Financing Costs are removed.

DISCOUNTING CALCULATIONS

Costs are discounted in line with the Guidance document from EA[7] and its supplementary note[8]. All cost components (including the calculated Financing costs) are discounted using the Treasury Test Discount Rate (TDR). Objective scores are also discounted using the TDR. 80 years of costs are used in the discounting calculations.

OPTIMISING THE PORTFOLIO

BASIC PRINCIPLES

The purpose of the DMF optimisation engine is to determine an optimum portfolio that defines:

- Whether a solution is selected
- Whether a solution is active in any year
- The proportions of the DYAA, NYAA and DYCP yields of active solutions that are required to meet demand scenario targets.

These are referred to as the decision variables.

An optimum portfolio may be defined as:

- The selection of options that meets the demand scenarios, solution constraints and any other portfolio-level constraints at least (discounted) cost
- The portfolio of options that maximises performance against other single objectives (e.g. operational resilience, environmental sustainability, deliverability, etc.) while still meeting the demand scenario, solution constraints and portfolio-level constraints.

The DMF Optimisation Engine represents the data solution data, solution relationship data and portfolio constraint data as a set of linear equations that are solved by applying Mixed Integer Programming techniques using the FICO XPRESS optimisation engine. Detailed documentation of these equations is available[9].

DEMAND SCENARIOS

Three required demand scenarios (one each for DYAA, NYAA and DYCP) are set as constraints for the portfolio. The scenarios cover 80 years (it is necessary to cover 80 years so that the variable costs for each option can be calculated from the calculated DYAA, NYAA and DYCP volumes for all 80 years). The selection of solutions into the optimum portfolio, the calculation of when they are active and of the % of volumes they provide is driven by the need to meet these demand scenarios.
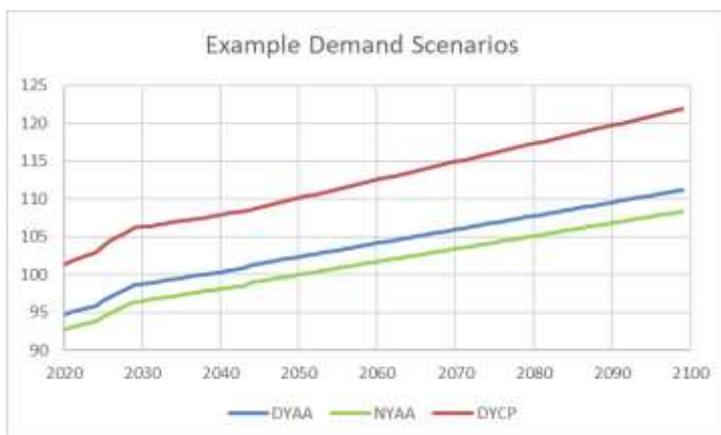

Figure 5 – Example Demand Scenarios for the Cambridge region

---

[9] Hartley McMaster Ltd, DMF Optimisation Model Version 6.0

MINIMISING COST

A minimum cost optimisation determines the portfolio of solutions that meets the demand scenarios (and any other constraints that have been applied) at minimum discounted Totex. A mathematical equation represents the total discounted Totex of a portfolio in terms of the decision variables. This becomes the Objective function of the optimisation. Solving the optimisation problem determines the values of the decision variables that minimise the value of this objective function.

MAXIMISING PERFORMANCE AGAINST MULTICRITERIA OBJECTIVES

The DMF optimisation model allows an objective function to be created that relates the total portfolio score against any single multicriteria objective (discounted) to the values of the decision variables. Solving the optimisation problem determines the values of the decision variables that maximise the value of this objective function.

OTHER PORTFOLIO LEVEL CONSTRAINTS

Other portfolio level constraints can be added to the optimisation problem:

- Minimum and maximum constraints on Totex and/or Capex and/or Opex in individual years or over longer periods (e.g. AMPs)
- Constraints on the maximum deployable output for each of DYAA, NYAA and DYCP in each year
- Minimum and maximum constraints against NPC (total discounted Totex) or total discounted objective scores.

The latter are particularly useful in that they allow questions to be asked such as 'what is the least cost portfolio that delivers a minimum score against operational resilience of 25?'.

MODEL OUTPUTS

The raw outputs from the optimiser are the values of the decision variables. Using these decision variables and the data defining each of the solutions, the costs and performance of the optimum portfolio can be calculated and reported.

The MIP methods that are applied to obtain the optimum portfolio also generate interim portfolios as part of the process. These are sub-optimal results that do, however, meet the demand scenarios. A least cost optimisation generates additional portfolios that are costlier but provide different portfolio level objective scores. These are of interest to decision makers as they identify how trade-offs against minimum cost may provide additional benefits against non-monetised criteria.

All costs, objective scores, yield, etc. can be output in spreadsheet form at a number of levels of aggregation. Data can also be output to enable users to generate Parallel Coordinate Plots and Pareto-curve type diagrams.

TESTING AND VALIDATING THE OPTIMISATION MODEL

One of the questions that is frequently asked of optimisation modellers is how they validate that the optimisation model and its results are correct.

The first thing to note is that the generation of the optimum portfolio from the optimisation equations formulated by the DMF optimisation model is performed by the embedded XPRESS optimisation engine, supplied by FICO. This is a commercial, off-the-shelf optimisation package that has been available in the marketplace for many years and undergoes comprehensive testing of its own before being released to that marketplace. Over the years those with an interest in optimisation (both academic and commercial) have developed suites of optimisation problems with known solutions. XPRESS is run against a number of these suites, to ensure it obtains the correct results and to benchmark its performance against competitor products.

If the correct equations are passed to XPRESS we can be sure that the correct results are returned. The purpose of the DMF optimisation software is to take the data passed into it and formulate equations for input into XPRESS. During the development of the software simple test cases were run that covered the types of optimisation and constraints included in the DMF. It is possible to obtain the equations used by XPRESS in a readable form as an output of the optimisation process. Such outputs were generated for the simple test cases and compared with the equations that had been specified and were expected. This enabled programming errors to be eradicated at an early stage. By formulating simple test cases it was also possible to determine manually what the expected optimum results should be. This provided a second level of testing.

Testing and validation activities are a regular part of the overall modelling process. Every time model results are obtained they are inspected to ensure that the results that are obtained make sense from a real-world perspective. This helps to assure that model data (particularly constraints between options) has been specified correctly.