AN OVERVIEW OF THE TRUNK SCHEDULING SYSTEM FOR THE LONDON RING MAIN

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ABSTRACT

The London Water Ring Main is one of UK's largest water investments. It will eventually carry half of London's water and greatly increase the flexibility of London's trunk distribution network. The Trunk Scheduling System is a core part of decision-support for the enhanced network. It has been written to help Operational Controllers make best use of that extra flexibility.

Cost-effective operation makes best use of the cheapest treatment works, low-energy-loss routes and off-peak tariffs. These need to be combined to meet projected diurnal demands in over 50 zones and leave each of some 20 service reservoirs at a target end volume, whilst taking no more than the declared "reliable output" from each of 10 works. The schedule proposed must be hydraulically viable as well as cheap. Most route constraints arise from pressure limits (so as not to burst mains or leave customers without water). Hydraulic constraints are non-linear and require on-line hydraulic intelligence as the schedule is developed.

The key idea is to regard a schedule as a series of "operating regimes", each of which is applied for a specified duration. Each regime applies within a particular timeslice. It comprises settings for each pump in the network, together with its implications: a unit cost and the effect of those settings on each source and each reservoir under hydraulic equilibrium. Trunk Scheduling provides a series of modules to answer the questions:

- which regimes (of the billions possible) should make up the schedule?
- how long should each selected regime be applied for?
- in which sequence should the chosen regimes be applied?

KEYWORDS

Water, distribution, optimisation, hydraulic equilibrium

CONTEXT

The London Water Ring Main is the largest investment by a UK Water Undertaking. It will significantly increase the flexibility of the trunk distribution network but impose a much greater requirement for integrated operation across London.
Thames Water is developing many new control systems in conjunction with the Ring Main, focused at the London Control Centre at Hampton. These include SCADA systems to monitor the current state of the network, and an Operational Management System (OMS) to bring the data together as the basis for managerial control. Coordination will be achieved from the Centre via Local Area Control.

Feeding off, and back to, OMS is a series of decision-support models. These help make best use of the flexibility which the Ring Main will offer and provide a basis for proactive management:

- demand prediction uses time-series data on past demand in each zone plus local judgement, to project demand for each zone;
- trunk scheduling starts with demand prediction and projected water treatment works outputs, and generate a schedule for all the major trunk distribution routes;
- area control modelling allows local areas to verify the hydraulic viability of the proposed schedule and fill in the local details.

The development of the Trunk Scheduling System - the core decision-support for the Ring Main - has been carried out in-house by Thames Water's Corporate Modelling Group, working closely with London Control staff. Ten man-years' modelling effort has been expended on the development. Much of the System is now in place and in operational use: the rest is undergoing calibration and operational testing.

Scheduling a hydraulically constrained network is an algorithmic task best tackled by well proven procedural methods. Rule-based systems may flounder when confronted with unexpected situations: this System needs to produce a solution whatever the circumstances. Algorithmic methods can still be used in an imaginative manner and in innovative combinations. Trunk Scheduling contains many imaginative leaps; this paper aims to explain these (in simple terms) and set them in the context of what the System has to do.

**REQUIREMENTS FOR TRUNK SCHEDULING**

**Cost-effective operation**

The Trunk Scheduling System's task is to help the London Control Centre develop daily schedules for the trunk distribution network. It has to find a cost-effective way of using the Ring Main and other major pumps, to deliver over 2000 Mld from some 10 water treatment works (or other sources) via 20 service reservoirs to 50 pressure zones.

**Boundary conditions and non-standard circumstances**

The schedule has to meet the day's expected "boundary conditions". These comprise the declared "maximum reliable output" for each works, the starting and target end volumes for each reservoir, and the demand (which varies significantly over the 24 hours) for each zone. All of these factors vary from day to day, so a specific schedule is required for each day.

Another reason for new schedules to be generated daily is that there are variations in the network itself. "Exceptional" circumstances include pumps being unavailable (e.g. for maintenance), stand-by pumps being deployed to a different duty/destination, infusions (i.e. flows achieved by adjusting valves between neighbouring zones with a pressure differential) and reservoir cells being taken out of service or having maximum or minimum levels reset.

**Hydraulic constraints**

The schedule must not only meet the boundary conditions and take account of the network configuration, it must work within operational constraints on how
much water can be delivered along each route at each time. The schedule must use pumps on their operating curves. It must not lead to pressures which are too high (burst pipes) or too low (unmet demand in higher parts of a zone).

The schedule must also make the best of variations in electricity tariff over the 24 hours. It costs much less to pump at night, so this is the best time to replenish reservoirs. However, the network constraints and the numbers of alternative routes mean it is not easy to work out the best way to do this.

KEY SCHEDULING IDEAS

Challenges for Trunk Scheduling

The requirements for Trunk Scheduling are not easily satisfied. The basic difficulty is that:

- the "constraints" on the flows which are possible depend on the hydraulic implications of the plan of action;

whilst

- the hydraulics (i.e. the hydraulic equilibrium of pressures and flows) cannot be computed until a plan of action has been proposed.

A further difficulty is the size of the network to be scheduled. Even when natural boundaries such as strategic reservoirs on the edge of the control area are taken as boundaries for Trunk Scheduling, there remains a vast area to be considered, which cannot easily be subdivided. This gives rise to a vast number of possible pump settings, far too many to be dealt with by (even enlightened) trial and error.

Various steps have been taken to overcome the difficulties and make the problem tractable.

Building in hydraulic intelligence

As a design principle, where constraints arise from hydraulic viability, it is better to make those calculations directly and as required, rather than rely on surrogate rules about what is possible. A hydraulic model offers the best form of hydraulic intelligence, if it can be incorporated within the system. Expert or rule-based systems are a poor substitute for direct calculation where the method of calculation is specifiable. Look-up tables (e.g. relating pressures to pump settings) may also seem attractive, but present formidable problems of maintenance as the network changes.

One innovative feature of Trunk Scheduling has been the development of a hydraulic model using optimisation methods. Because optimisation occurs elsewhere in the System, this has made for economical and compact coding. The approach has turned out to be better at sensitivity analysis than conventional hydraulic methods, allowing pump setting variations to be rapidly evaluated.

Development of a schematic network

To apply a hydraulic model, a schematic network is needed for the Trunk Distribution network. Another design principle is that the same network be used for all stages of scheduling. Doing this minimises on-going maintenance of the System and makes it easier to use. Considerable effort has gone into developing a schematic which captures the key control and transfer elements of the London network.

Time slicing

An important idea to help break down the problem was to schematise time by
introducing "time slices" and not allowing boundary and tariff conditions to vary within a timeslice. Currently seven timeslices are assumed, namely night, rising (both customers and demand!), peak, morning, afternoon, teatime and evening. These allow the diurnal variations in demand and in tariffs to be handled with an acceptable level of accuracy.

Basic schedule building blocks: regimes

Given a hydraulic evaluator, a schematised network and a day divided into homogeneous timeslices, the key idea of Trunk Scheduling comes into play. This is to regard a schedule as being composed of a series of "operating regimes", applied in a particular order and each lasting for a specified duration.

Each "regime" comprises:

- a list of on/off and speed "settings" for each pump in the network;
- its overall energy use, taking account of the efficiency with which each pump will perform when this regime is applied; and
- details of what "impact" that regime will have on the network.

Each regime operates in a particular timeslice, for which the boundary conditions (supply and demand) are known. When the pump settings are applied to the network, the resulting equilibrium will include an effect (either filling or emptying) on each reservoir and a usage figure for each works. These consequential impacts are an essential part of the regime.

For Trunk Scheduling, regimes are the key building blocks for a schedule. Once the regimes themselves have been specified, a schedule can be specified very compactly as a list of "regimes" and "durations".

A key virtue of dealing with regimes is that their hydraulics can be accurately evaluated and costed (and indeed must be, so the reservoir fill rates can be assessed). Hence, one can avoid considering any regime for the schedule which would not be hydraulically acceptable. Furthermore, if a schedule is made up of regimes which are individually viable, it will in turn be acceptable provided it has the right cumulative effect on each reservoir.

Once regimes are specified together with their reservoir implications, it is a matter of arithmetic to compute the reservoir profiles that will result from a particular schedule. If the cost of each regime is known, it turns out to be a straightforward linear programming (LP) problem to find the best "blend" of a given set of regimes to bring reservoirs to their target end volumes at minimum overall cost.

The concept of "regime" is crucial to Trunk Scheduling. Essentially, London is regarded as being controlled by a series of pump settings, each of which is operationally viable, and which have the right effect in combination. With 100 pumps in the schematic network, however, there are several billion billion possible regimes. Identifying the best of these and showing how they should be combined together is the central task for Trunk Scheduling.

COMPONENTS OF THE SCHEDULING SYSTEM

The Trunk Scheduling System which has been developed to meet these needs comprises a number of separate modules, which can be combined in various ways. The models are depicted in Figure 1, and are discussed in turn below.

The System is written in Turbo Pascal. The system comprises some 120,000 lines of code and comment and the executable code occupies some 900K.

Setting boundary conditions and overall allocations: NETPLAN

The first task of the Scheduling System is to check that the overall boundary conditions for the day's schedule are consistent and achievable, and to gain
an overview of the way the flows will be allocated.

The boundary conditions comprise:

- "supply" - each water treatment works' declared reliable output;
- "demand" - the projected diurnal demand for each Zone, based on recent trends and local judgement;
- reservoir starting levels and "target end levels" for the schedule.

The "exceptional" features of the network also need to be established so they can be taken into account in this and all subsequent modules.

Clearly, one must ensure works availability exceeds demand plus reservoir refill. It is also be necessary to take account of flow constraints within the network and variations over the day. There are many problems where there is an overall excess but local shortfalls - for example, excess supply in northeast London cannot necessarily be transferred to a zone in the southeast.

The module to check the day's boundary conditions is called NETPLAN and is always called first in Trunk Scheduling. It does not have access to the hydraulic assessor, but relies on user-specified flow constraints on each route in each timeslice. Pump capacity constraints are expressed as an estimate of the lift required of each pump in each timeslice, which are then translated (via pump characteristic curves) into flow constraints.

NETPLAN has to take account not only of the flows along routes but also the scope for using the service reservoirs to smooth out the variations in demand over the day and to maximise cheap pumping. To do this, the flows for the whole day need to be considered together. This is done by considering a multi-tiered version of the schematic network, with one "tier" for each timeslice. The operational flexibility offered by the reservoirs is then incorporated by adding notional arcs between each reservoir in successive timeslices, the capacities of these "routes" being determined by each reservoir's storage limits. A stylised version of the enhanced network is depicted in Figure 2.

When the 300-arc schematic network is replicated seven times (for each timeslice), notional arcs are added between each of 20 reservoirs in each timeslice and boundary links are added in for each source and each zone, a network of some 2,500 route "arcs" and 1,000 location "nodes" is obtained.

Unit costs on each of these arcs arise from the marginal costs of treatment at a works or from the energy use of each pump in achieving its assumed lift (given its operating curve). NETPLAN applies network optimisation to find the cheapest set of flows to meet the specified demand over the day, keeping within route capacities and making best use of the service reservoirs.

The problem is a special case of linear programming. A fast method of solution is used, called Network Simplex. This uses a sophisticated labelling scheme to rapidly improve an initial "solution". The NETPLAN code solves the problem specified, on a 486 PC and starting with zero flows, in under 10 seconds.
The NETPLAN solution flows are optimal in several ways:

- they make best use of the sources available - all other factors being equal, the solution will minimise use of the least efficient works;
- they make best use of the pumps, taking account of their efficiencies and of the costs of alternative routes into zones;
- they make best use of reservoirs to time-shift as much pumping as possible to the low-tariff periods.

Because NETPLAN can solve the problem so quickly, it can be used as a "what-if" tool to investigate the effects of alternative boundary conditions. This is particularly useful on days where demand is high or supply restricted, and some adjustment to the initial boundary conditions is required (e.g. upping a works output, or reducing an end-of-schedule reservoir target).

"Infeasibilities" arise when supply and demand are out of balance. They manifest themselves in hard-to-reach zones which may not be the real source of the difficulty. NETPLAN handles these problems in an intelligent manner. This is done by building in additional notional arcs when setting up the multi-tier network, with a high unit cost, at points where constraints might need to be relaxed. By graduating these penalty costs, NETPLAN is made to break its constraints (where necessary) in a controlled manner. Hence even "infeasible" solutions give sensible guidance to the user on the best way to modify the day's boundary conditions so the scheduling problem can be solved.

Calibrating standard regimes to the day's boundary conditions: NETSIM

The NETPLAN solution, for all its usefulness, falls short of being an achievable pump schedule. This is for the following reasons.

- It recommends average flows by route and timeslice. The way that pumps should be deployed to achieve these flows is yet to be determined.

- NETPLAN uses flow constraints as surrogates for pressure limitations. This is acceptable for checking overall flow allocations, but means one cannot be sure that a particular set of pump settings will not burst mains or leave customers with inadequate pressure.

In order to build a schedule to meet the agreed boundary conditions, it is necessary to start, not with the NETPLAN flows, but with sets of possible
Trunk Scheduling System

operating regimes as the basic building blocks for the schedule.

Trunk Scheduling exploits the fact that successive days are likely to be fairly similar from a scheduling viewpoint. A reasonable starting point for a schedule is to take yesterday's schedule and consider how it needs modifying to meet today's requirements. More specifically, breaking yesterday's schedule down into a succession of pumping regimes, one can ask:

- what will be the effect of these regimes taking account of today's new boundary conditions and plant availability (and zonal infusions)?
- given an updated implication for each regime on reservoir fill rates, how should the regimes be deployed so as to leave each reservoir at or above its target volume by the end of the schedule period?

The first of these questions is dealt with by the NETS 1M module: the second is covered by the NETBLEND and NETBUILD modules.

NETSIM's task is to hydraulically simulate a possible set of solution regimes on the latest boundary conditions (for supply and demand), taking account of plant availability and other exceptional circumstances. For calibration purposes, each equilibrium is computed at a standard mid-timeslice volume for each reservoir: this enables regimes to be compared on a like-for-like basis (when NETSIM is re-visited at the end, cumulative volumes are computed).

Finding a hydraulic equilibrium is a standard problem for which long-standing solutions exist. However, Trunk Scheduling needs to find the equilibrium heads and flows for each regime within an integrated system: it would be unwieldy to do this by recourse to an external package. Instead, it uses a method for solving hydraulics via optimisation, suggested only in the late 1970s.

The node "dual costs" used by the Network Simplex algorithm when optimising turn out to correspond in this case to the head at each node. It is surprising to find an internal working variable with real physical significance! This means that the approach can be extended to allow rapid inspection of heads at nodes at equilibrium, and hence of hydraulic viability.

As with NETPLAN, it is possible to make the program react sensibly to unacceptable solutions. This is done by stating, for each critical-head node, a responsive manifold to deal with any violation. Where a head constraint is infringed, the relevant pump settings are then "trimmed" to deal with the infringement and a new hydraulic equilibrium sought.

A set of regimes can be run through NETSIM and hydraulically evaluated on the relevant boundary conditions. Where necessary, pumps are automatically fine-tuned to avoid hydraulic violations. The total pump usage and consequential refill rate of each reservoir passes through to the next stage of calculation.

Finding the best blend of regimes: NETBLEND

Given a set of valid regimes, Trunk Scheduling next asks what is the best way to combine these so as to achieve the target reservoir volumes by the end of the schedule, keeping each reservoir in bounds at the end of each timeslice?

Because the effect of each regime on the reservoirs is known and each timeslice is homogenous, this can be answered using linear programming:

- the variables to be found are the durations spent operating each regime (which could be zero for some of the candidate regimes);
- the constraints are the upper and lower bounds on the cumulative volumes for each reservoir at the end of every timeslice, plus the requirement that enough regimes are used to totally account for the hours in each timeslice;
• the objective function to be minimised is the total cost of operating with the selected regimes and durations.

With 20 reservoirs and 7 timeslices, this leads to a fair-sized problem with nearly 300 constraints. However, nearly all of the constraints occur in pairs, so one can use "bounded LP". The number of constraints is halved and extra information carried about whether non-basic variables are at their upper or lower bound. Halving the number of constraints gives an acceptable solution time (4 minutes on the Control Room 486). This type of short-cut makes it sensible to use purposely written code (which can be linked to other modules) rather than accessing a commercial package.

The formulation aims for reservoir end-volumes by imposing penalty costs where these targets are missed, rather than absolute constraints. This gives end targets the status of "soft constraints" - a realistic view, given the variations between predicted and actual demand which will occur before those targets are reached. NETBLEND can then suggest schedules which fall below the end targets if it does not have the regimes needed to hit them all exactly.

NETBLEND is involved in much the same optimisation as NETPLAN. It too knows about variations in tariff between timeslices, in treatment costs and in aggregate pumping costs for alternative regimes. Hence it is no surprise that NETBLEND gives rise to similar reservoir profiles to NETPLAN.

Generating additional regimes: NETBUILD

The limitation of NETBLEND lies in the pre-selection on the regimes it can choose between. To overcome this, another module, NETBUILD, allows "switching" in of new candidate regimes, once an initial solution has been found.

There are two key observations.

• If a regime is not used in a NETBLEND solution, it can be replaced in the LP by another without affecting the current solution, after which the search for a better solution can resume. This will lead to a schedule making use of the new regime if it is cost-effective to do so.

• Marginal cost information for a NETBLEND solution gives insight into the most costly aspects of making up a schedule using the given regimes. Marginal costs show the benefit that would accrue if each constraint could be relaxed. Because constraints apply for each reservoir, one can derive a marginal cost for filling each reservoir in each timeslice, given the current solution.

The task of the NETBUILD module is to complement this process by generating a suitable regime to add to the current schedule in the light of the marginal fill cost for each reservoir. (A special case of this requirement is where the original regimes are insufficient to generate a feasible schedule at all.) The relationship between the NETBLEND and NETBUILD modules is depicted in Figure 3.

The extra candidate regime has to be operationally viable and hydraulically evaluated: hence it needs to be derived using the hydraulic assessor. The Trunk Scheduling System needs to be able to alternate between a substantial linear program and a hydraulic model for the whole of London as:

• NETBLEND tries out extra regimes and moves to a new solution; and
• NETBUILD finds another regime to improve on the current solution.

Some complex overlaying is needed for this to be achieved, only possible because source code for all aspects of the System is available.

The NETBUILD module needs to identify which pumps to switch on or off in the
light of marginal reservoir costs, which convey information about which reservoirs it would be profitable to replenish and which to empty, in the context of the current solution.

If there were a simple link between reservoirs and pumps, with each reservoir controlled by a single set of pumps, this task would be easy. However, there are many more pumps than reservoirs, and (via the hydraulics) many links between the two types of element. In particular, changing the pumping at a works manifold can change the fill rate of several reservoirs. The Ring Main itself, as a low-resistance route connecting different parts of the network, increases these interactions.

To identify a suitable regime requires information on the effect of each pump on each reservoir. This is done using "Impact Tables". Impact Tables state the marginal effect of turning on each pump on the instantaneous fill rate for each reservoir and source. This "gradient information" is used to guide the search for a new regime.

Converting a NETBLEND solution to an operational sequence: NETSEQ

The interchange between NETBLEND and NETBUILD continues until the user is satisfied. At this point the "solution" consists of a series of regimes, which if run for specified durations will ensure that the reservoirs are in bounds at the end of every timeslice and meet their end-of-schedule target.

Some work is still needed to move from this to a viable schedule because:
the order in which the regimes appear in the solution takes no special account of pump switchings or variations in Ring Main flows or water treatment works outputs, and it is desirable for these to be minimised;

- whilst all reservoirs are in bounds at the end of every timeslice there is no guarantee they will stay in bounds within the timeslice.

The task of turning the NETBLEND solution into an operationally viable schedule is carried out by the NETSEQ module. NETSEQ has no control over the regimes chosen or their total duration, but it can adjust the order in which they appear and whether the regime is applied once, for its full duration, or split into a number of shorter spells.

Splitting a regime adds to the pump switches incurred, but makes it possible to keep all the reservoirs in bounds throughout a timeslice. It may be needed, for example, where two regimes have opposing effects on some of the reservoirs, and need to be operated alternately to keep all of them in bounds.

The order in which regimes appear in the schedule needs to be adjusted so as to minimise pump switching and key flow variations. Since the pump settings for each regime are known, it is easy to find the number of pump switches and flow jumps incurred for any specified sequence.

The task of finding the sequence which minimises overall pump switching is analogous to the "Travelling Salesman Problem". In this, the salesman has to find the best tour of a number of cities so as to visit each city once and minimise the total miles travelled. The cities to be visited correspond to regimes. The mileage incurred is the pump and flow switches needed to move from one regime to the other.

A standard way to solve the Travelling Salesman Problem is to try random swaps and inversions of part of the "tour", and keep track of the best sequence found. Ideas from "simulated annealing" are used to avoid getting stuck in a local minimum. Trunk Scheduling applies a similar technique to move to an acceptable sequence or regimes. One benefit of the heuristic approach is that it can ensure reservoirs stay in bounds. Another benefit is that it lends itself to manual intervention if required.

Illustrative results from a call to NETSEQ are shown in Figure 4. The top panel shows profiles for 18 reservoirs and the middle one the variations expected in works outputs, with the schedule proposed. The pumps to be switched during the schedule are shown in the bottom panel. The schedule is made up of some 21 pumping regimes: each vertical line marks the start of a new regime.

Testing and tuning the final schedule: NETSIM revisited

Once NETSEQ has been run, the NETBLEND solution has been converted to potential schedule; this is sent back to NETSIM for final verification.

The schedule comprises regimes chosen to make best use of lower-cost sources, low-energy-loss routes and cheap tariffs, and with durations and an order which ensures all reservoirs will stay in bounds and meet their end targets.

Since only operationally viable regimes are offered to NETBLEND, this schedule should be operationally viable. It is necessary to simulate the schedule taking account of cumulative reservoir volumes when regimes are run in schedule order. Extensive and powerful editing facilities are provided for the Controller to fine-tune the schedule as required.

CONCLUDING OBSERVATIONS

NETPLAN was in the London Control Room for its Royal Opening in January 1992.
A major calibration exercise was undertaken by Operations to check the NETPLAN-recommended flows are in line with those achieved in practice. The interface has been refined following users' suggestions.

NETPLAN has encouraged Operations to formalise procedures relating to the data needed to run the model. Control staff have had one-on-one support from a Corporate Modeller based at the Control Centre. Confidence in NETPLAN is growing and its status is moving from background advisor to a core Control Room System.

The remaining modules were delivered for operational testing in November 1992. An extended handover is now underway, including formal training and calibration.

The London trunk distribution network is a complex facility, undergoing rapid change. The history of the project has been one of intellectual and organisational challenge. Operating the Trunk Scheduling System is likely to throw up many new questions for investigation. However, the solid basis for the System described in this paper is the best guarantee available that the future challenges will also prove surmountable.

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