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SAVING COSTS IN OPERATING PRESSURIZED WATER SUPPLY SYSTEMS

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SUMMARY – The electrical power required for operating a pressurized water-supply system is a major factor in water costs. This paper presents a method for optimizing pumping energy costs. It is designated for large, computer-controlled water-supply systems. The software tool that is based on this method is an integral part of an automatic control system, which is used for designing and updating the operational schedule in real-time. In order to optimize the energy cost, the method takes advantage of two basic conditions: (1) the cost of electrical energy varies throughout the day, and (2) the water system includes storage capacity, which enables a separation between the tight connection between source pumping time and consumer supplying time. The algorithm calculates an optimal operation schedule, characterized by shifting pumping time as far as possible into the low energy cost time period of the day. This is done while preserving the reliability of water supply. As part of the whole process, the optimal operation is calculated, using linear programming (*L.P.)* algorithm*.* The whole process consists of three main parts: (1) factoring the engineering problem of schedule design into the mathematical model of the *L.P.;* (2) reaching the optimal solution by using the Simplex method; and (3) interpreting the mathematical result into the operation schedule. The schedule data are transferred to the central control database, for execution by the automation system.

Keywords: energy saving, water supply system

1. WATER DISTRIBUTION SYSTEM MODEL

1.1. Description

A pressurized water distribution system must sustain two hydraulic demands: water flow – which is controlled by the water network consumers, and head pressure – which is required by the consumers at the supply locations. The model of the system consists of links, nodes and hydraulic components which enable water conduction from sources to consumption nodes. The figure below illustrates how these objects can be connected to one another to form a network.

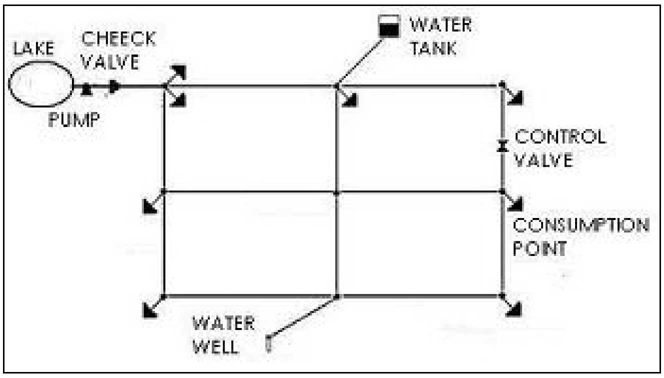


Figure 1. Pressurized water supply system

1.1.1. Water demand

The water demand flow distribution is controlled by the consumers, and the pumping operation schedule must supply this demand. Therefore, the expected demand distribution plays an important role in the design process. Expected demand is calculated using standard statistical utilities that analyze the ‘historical’ instant flow and derives a forecast of demands for the next operation plan interval (the expected water demand forecasting method is beyond the scope of this lecture).

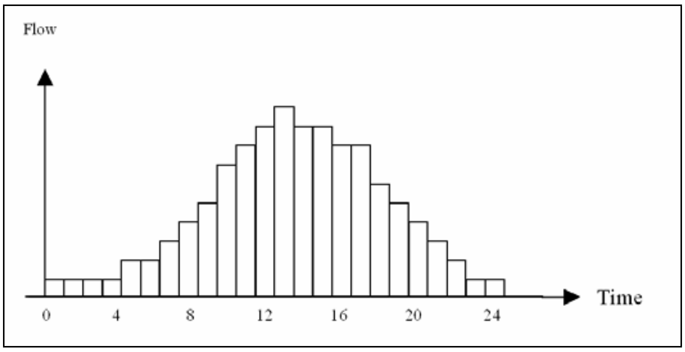


Figure 2. Typical curve of domestic water demand distribution over the day

1.1.2. Water tanks

The pressurized water distribution systems must meet the peak water flow demand of the day, in the highest demand season of the year. As shown in Figure 2, the peak time duration in the day cycle is relatively short, while the flow demand during the rest of the day is significantly lower. Therefore, a direct supply from the water sources to the consumption points requires high pumping capacity and large diameter pipelines: and approach that yields an expensive network which impacts on the water cost. To avoid this, most of the pressurized water distribution systems include water tanks that are used for operative storage. The water tanks are located near the main demand zones in topographically high areas, and store the excess water that is pumped at low demand periods. During the high flow demand, the tanks are used as ‘local water sources’ and regulate pumping and conduction from the sources. The tanks are designed according to the criteria of maximal consumption, which is required only during the high season of water demand.

For the rest of the time, there is an extra storage, pumping and conduction capacity.
The optimization method utilizes the extra storage, and optimizes the pumping energy cost.

1.1.3. Pumps and pumping energy cost

Most water sources, lakes, rivers and especially underground aquifers, are located at lower topographic levels than the consumption points. Moreover, pressurized supply systems must supply the flows and head pressures required by consumers. Pumps raise the water’s hydraulic head and enable the flow from a low topographical level to a higher one. The operation of the pumps consumes external energy, usually electric energy, and its cost is the major factor in water cost. The main purpose of the discussed method is to decrease pumping energy costs to the minimum. What makes it possible is the fact that electrical facilities around the world charge different rates for electricity consumption throughout the day. In some cases, the ratio between the lowest and highest rate is 1:4.

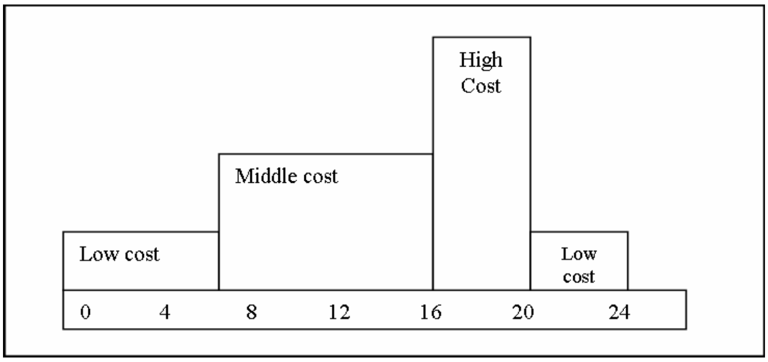


Figure 3. Daily energy tariff

2. OPERATION

2.1. Manual operation

Traditionally, systems were operated manually. The water facilities' operators used to manually control every pump in the network. This mode of operation requires a large 'safety overhead' of water storage, to ensure that the water level does not drop below the low-level mark and risk water supply reliability. In economic terms, this mode of operation is very inefficient and results in high-energy cost payment.

2.2. Automatic control

Over the past two decades, automation and control have been integrated into water supply systems, enabling real-time readings of the hydraulic state of each element in the system, and remote control by various devices such as pump and control valves. The collected data can be displayed and stored in databases. It can also be monitored, and operation commands can be transmitted back to the elements in the field. Having all the collected data at a central location enables operational decisions to be made.

2.3. Automatic operation by set-points

The 'set-point' method is based upon a set of previous conditional instructions for each operational device (pumps, valves, etc.). Each instruction relates to some hydraulics parameters, called 'set-points'. The instructions dictate the action that should be taken when the hydraulic instant rate reaches the set-point given value. There are various disadvantages to this operational method, and this is especially true in cases where several pressure zones are connected to the same sources. The main defect is due to the lack of an 'overall system view', resulting from the fact that each element in the system is operated by the given set-points regardless of the other elements. In large and complex water systems, this effect becomes more significant. Moreover, the system is purely empirical, and is based on the experience of the facility operators' intuition. Using the set-point method for large, complex water systems usually leads to an ineffective operation process. Even worse, it might lead to impossible supply conditions that do not meet the consumer's requirements.

In addition, the method requires a very frequent updating of the set-points' values, which is needed in the case of modifications in electric cost, the demand distribution, or pump failures.

The overall inefficiency of the set-point method stresses the need for a new method that creates an operation schedule in a short time and updates the program in real-time.

3. THE METHOD FOR OPTIMAL OPERATION PLANNING

The design goal and the planning process are aimed at finding the lowest energy cost for the feasible pumping schedule for a given period of time.

3.1. Prerequisites, conditions and system infrastructure

In order to implement the method, the water network must include the following features:

- Operative storage,
- Automation control,
- Water demand forecast modules.

3.2. Optimization tool

The operation algorithm is based upon the Linear Programming (L.P) method. It can be applied to any optimization problem which can be formulated as a set of linear equations, and a target function that defines the weights of the decisions variables. The following is the formalization of the L.P. model in mathematical terms:

A set of linear restrictions

$$\sum_{i=1}^{M}\sum_{j=1}^{n} A(i,j)X(i)(<or=or>)B(i)$$

$$X(i) \geq 0$$

A target function

$$Z_{i=1}(max or min) = \sum C(j)X^{n}(j)$$

While:

X(j): decision variable
A(i,j): Known coefficient
B(i): right hand side of the restriction (known value)

Solving an L.P. problem is an iterative process, performed using converging methods such as the Simplex algorithm.

4. FORMULATION OF OPERATIONAL PLANNING AS A L.P. PROBLEM

Following is a representative figure of a pressurized water supply system used in the formulation explanations and the operation plan process demonstration.

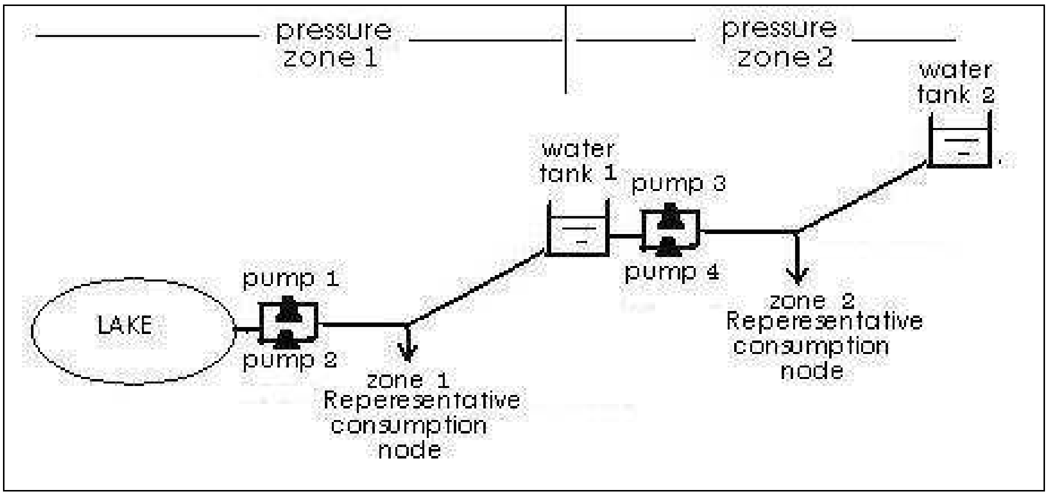


Figure 4. Illustrative model of two pressure zones

4.1. Initial preparations

4.1.1. Sub-period division

The operational planning is divided into a sequence of sub-periods that cover the entire planning time period. The division must be made in such a way that the energy cost remains uniform for the entire duration of the sub-periods.

Figure 5 demonstrates the method of determining the sub-periods

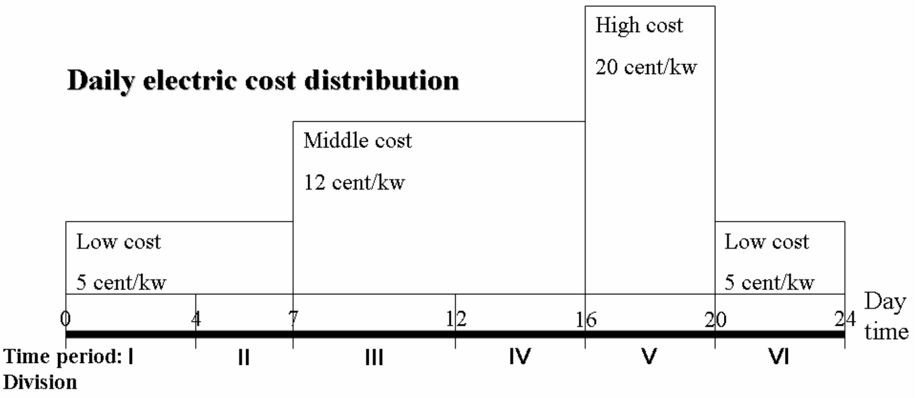


Figure 5. Division of the design range time into sub-periods of time

The sub-period data are presented in Table 1.

Table 1. Time period table

Time period	I	II	III	IV	V	VI
Start time	0	4	7	12	16	21
Final time	5	7	12	16	21	24

4.1.2. Physically feasible operating pumps combination

For a pump station with several pumping units, the model requires data on the feasible pumps combination. The table below presents an example of pump combinations in the illustrative model (Figure 4).

Table 2. Pump combinations, flows and energy consumption

Pump combination No.	Pumps in combination				Flow (m^3/h)	Energy consumption (Kw/h)
	1	2	3	4		
1	x				150	50
2		x			200	60
3	x	x			330	110
4			x		100	33
5				x	150	50
6			x	x	235	90

4.2. Decision variables definition

The decision variables X(i) are the operating time of each pumps combination in each sub period.

The total number of the decision variables is:

$$Ndv = Npc \times Nsp$$

Where:

Ndv: number of decision variables
Npc: number of pumps combinations
Nsp: number of sub periods

4.3. Inequalities (restrictions) set definition

The inequalities define the range of the solution's feasibility. Each combination of the decision variables X(i), I = 1 to Ndv, which fulfil the inequalities set, is a feasible mathematical solution.

There are four groups of constraints:

- Group 1 ensures the upper level of the water tanks; inflow into the water tanks will not cause the water to overflow.
- Group 2 ensures the lower level of the water tanks; the outflow from the water tanks will not cause the water level to drop below the low-level mark.
- Group 3 ensures that that the final water level at the end of the last sub-period in the tanks will be equal to a given value.
- Group 4 ensures that the total operation time of all the pump combinations related to a sub-period time will not exceed the sub-period time.

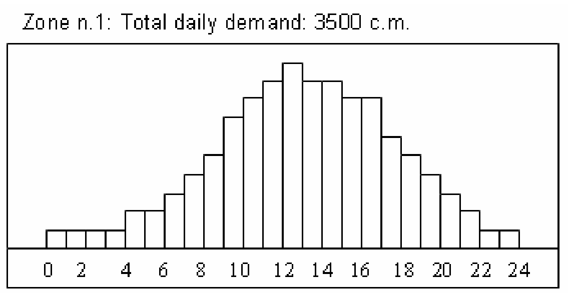
4.3.1. Restrictions coefficients values

The coefficients A(i,j) of the restrictions is the flow rate of the pump combination, shown in Table 2.

The data used to determine the R.H.S. (right-hand side) of the inequalities set are water-tank data (Table 3) and the forecasted water demand distributions of the pressure zones (Figure 7).

Table 3. Water tanks data

Water tank number	Section area (m^2)	Initial water volume (m^3)	Minimal water volume (m^3)	Maximal water volume (m^3)	Final water volume (m^3)
1	300	500	300	1800	500
2	250	400	250	1500	400



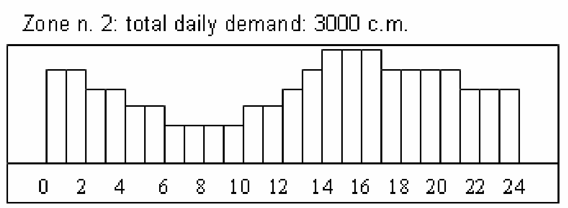


Figure 7. Forecast water demand distribution

4.3.2. The target function

The target function presents the total energy cost for the design period. The decision variables' coefficient value C(j), is the energy consumption of the pumps combination (Table 2) multiplied by the energy cost of the relevant tariff. Each feasible solution has its objective function value. The target is to minimize the energy cost, and therefore the target function is a minimization function:

$$Z(min)=\sum_{i=1}^{n} C(j)\,X(j)$$

Once the operational planning problem is defined as an L.P. problem, the optimal solution is attainable.

5. PLANNING SAMPLE

5.1. The model and the input data

A computer software based on the discussed planning method was operated to determine the optimal operation schedule of the pressurized water distribution system, described in Figure 4.

The planning is based on the following input data:

- Planning range time of 24 hours, starting at 00.00 and terminating at 24.00.
- The sub-time periods (6), determined for the model (Table 1).
- Feasible pump combinations, their flows and energy consumption (Table 2).
- Water tanks volume data (Table 3).
- Forecasted water demand distribution of each pressure zone (Figure 7).

5.2. Planning results

The planning result presents an optimal operation schedule expressed by:

- On/off pumps time table for each pumping station
- A graphical description includes the following result information:
  - The expected water tanks curve level on time scale, calculated according to the planning operation schedule, water demands distribution, and initial water volumes of the water tanks and the water tanks section area.
  - Pumps on/off description, on time scale, according to the planning operation schedule.
  - Energy cost tariff, description of on time scale

Table 4. Pumps operating schedules

Pump station n°1			
From hour	Until hour	Pump n°1	Pump n°2
00:00	01:28		x
01:28	07:00	x	x
07:00	10:26		x
10:26	16:00	x	x
16:00	21:00		
21:00	24:00		x

Pump station n°2			
From hour	Until hour	Pump n°3	Pump n°4
00:00	04:00	x	
04:00	05:00	x	x
05:00	06:19	x	
06:19	07:00	x	x
07:00	11:00	x	
11:00	12:00	x	x
12:00	20:00	x	
20:00	21:00	x	x
21:00	22:20	x	
22:20	24:00	x	x

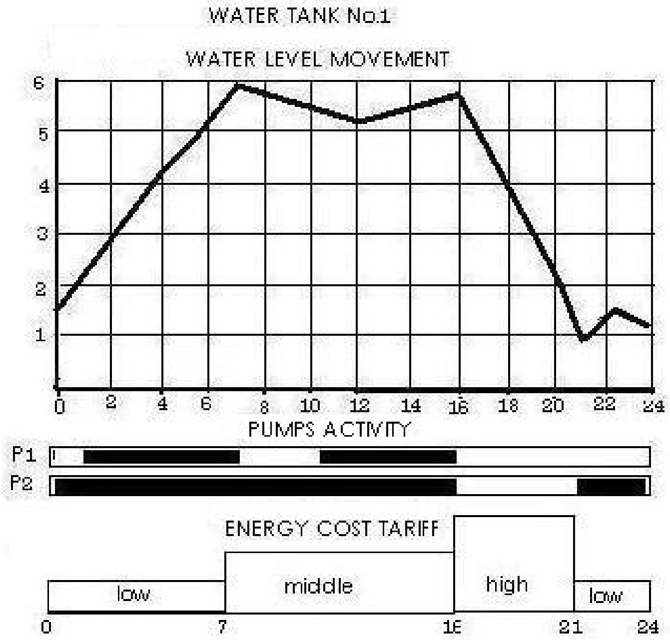


Figure 8. Water tank no.1: water level movement

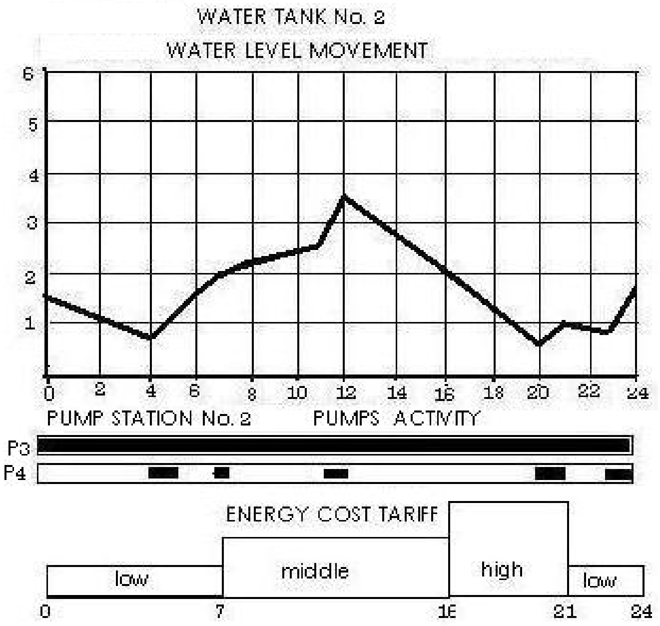


Figure 9. Water tank no.2: water level movement

6. ASSIGNMENT OF THE PLANNING OPERATION SCHEDULE IN AUTOMATIC OPERATION PROCESS

6.1. The schedule planner software

The operation planning method has been implemented into the schedule planner software. The required input is the instant hydraulic state of the water distribution system and the forecasted water demand.

The output is pumps on/off time schedule (Table 4), and additional general information about the planning procedure of the water system, especially the tanks water level movement (Figures 8 and 9).

The accuracy standard of the planning procedure of the water system depends on the accuracy level of the input data, especially of the forecasted water demand data. In a case of high data accuracy, the real hydraulic proceeding should be identical to the planning proceeding of the water system, during the all-planning range time. In practice, there is some deviation in the input data which causes deviations between the real and the planning hydraulic state. In particular it is expressed by deviations between the actual and the planned water level in the water tanks.

6.2. Implementation of the software in automation control

The mentioned deviations between the planned and the actual hydraulic states require an updating of the operation schedule. The updating process is achieved by combining the schedule planner software with the automatic control software package, using the automatic control database as a connector element.

The combined software working mode is as follows: the schedule planner software creates an operation schedule and saves it in the database for current operation of the automatic control system. Next, the automatic control system scans the measure devices of the water system every few minutes, and saves the data in the database. The schedule planner software receives the hydraulic scan data and compares it with the prevision hydraulic data. In the case that the deviation between the compared data is higher than the given rate, the schedule planner software uses the last instant hydraulic data as an input and calculates a new operation schedule. The new schedule data are saved in the database, and are used by the automatic control system for the current water distribution operation.

7. SUMMARY

The discussed optimal planning method may be applied in the automatic operation of pressurized water distribution systems, especially in large and complex ones. Its greatest advantage lies in the global observation over a period of time. This planning approach ensures high efficiency and reliable operation, even in cases of problematic water-supply conditions.

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