POLITECNICO
MILANO 1863

Course of "Industrial Hydraulics" A.A. 2025-2026

Project:

Improving WDS operation with a 5-years investment and management plan

Case description

The network under consideration is affected by intermittent supply and high leakage level. Intermittent supply means that water is not continuously available for all the users of the network. It is a problem that affects about 1.3 billion people worldwide. The user is considered as unserved when the pressure at his delivery node is below a certain limit.

Project Scope

The scope of the project is about establishing the strategy for the rehabilitation of the network using a fixed amount of money to be invested yearly over 5 years (320’000 €/year). The rehabilitation level is estimated using some performance indicators defined in the following. The objective is to reach the higher number of completely satisfied users (with continuous water supply), to improve energetically the system (reducing if possible, energy consumption), to reduce water leakages (improving leakage repair), to install a monitoring system (highlighting potentially critical areas).

Students will present six different operating scenarios: the initial state (corresponding to the first year in which no investments are made, but only operation on existing devices) and 5 scenarios for each year of investments.

The available simulation data are reported in:

- an .inp file that contains the network scheme, the user base demands, the pattern (168 hours characteristic for the entire year), the emitters (leakage).

- an excel file that reports the leaking pipes, the leak entity, and the leak position

Restrictions

- The layout of the network must remain the same, new connections can’t be created.
- Maximum yearly investment is equal to the yearly budget. Budget not used in the year is lost.
- Pumps can be replaced, but they must lay in the same node.
- Diameter of the valve must be as close as possible to that of the pipe on which it is installed. To add a valve a new node can be created.
- Valves may only be installed on existing pipes.
- The natural springs and wells have a maximum flow rate (MFR) that can be extracted that is reported in table. This maximum flow rate can’t be overcome at any time in the project.

Source	Type	Head (m)	Max Flow rate (l/s)
R1	Spring	164.95	200
W2_SA	Well	58	10
W3_AB	Well	52	25
W4_SM	Well	32	48
W5_PL	Well	25	27
W6_NORTH	Well	22	58

  In the case of spring, the water head is the level of the reservoir that collects the water and supplies it to the network. In the case of wells, the water head represents the diurnal water level elevation of the well.
- W6_NORTH is not connected to the network, it necessitates of a dedicated pipeline to be connected to the network (connection is not mandatory).
- Velocities in pipes should not exceed 2m/s.
- The budget that is not spent in a year is lost.

Initial state of the network

The students must initially propose a suitable mode of operation that, in accordance with the network's capacity, allows the largest possible number of users to be supplied for the longest possible time. To do so, they can operate on the statuses of the network elements (existing valves, existing pumps, etc.). Pipes that are initially closed can be opened without cost.

None of the existing pumps is equipped with frequency inverter, thus their velocity can't be tuned but pumps can be switched on and off with simple controls without costs.

Allowed operations

Only after year 0, investments can be planned. Operations allowed are those defined in the cost estimation section. Moreover, all operations that do not have a cost can be planned without limitation like (introduction of simple controls, change valve operation, change status of closed pipes)

On hydraulic simulation

The simulations are pressure driven analysis (PDA) in which the behavior of the users will be represented as pressure-dependent demands. Specifically, the representation of the demand at a node i (qD,i) will be given by the expression (Wagner et al., 1988):

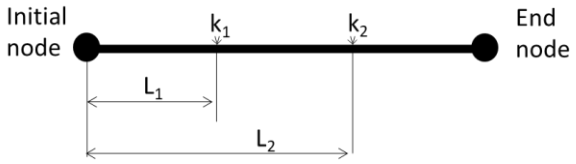
$$q_{D,i} = \left\{ \begin{matrix} D_i & p_i \geq p_f \\ D_i \left(\dfrac{p_i - p_0}{p_f - p_0} \right)^{\frac{1}{e}} & p_0 < p_i < p_f \\ 0 & p_i < p_0 \end{matrix} \right\}$$

For all consumption nodes the following parameters shall be considered fixed:
• P_0 = 0 m (= pmin in simpleSim.m)
• P_f = 10 m (= preq in simpleSim.m)
• $1/e$ = 0.5
Only the demand D_i will vary from node to node.
The values P_0 and P_f are necessary to define the functioning of the pressure-dependent consumption model that is used to represent the behavior of the users. However, the local by-laws of the supplied municipality consider $P_{ref} = 20m$ as the minimum acceptable pressure to consider a quality supply.

The operation of the network is the same for all the 52 weeks of the year. However, it will change from year to year depending on the investments made and the changes in the way the network is controlled. The six hydraulic simulations (initial state and situation after each of the five years of investment) are considered to be independent. The initial state and setting of the elements (pumps, valves, lines) may be different in each of the six scenarios.
The desired weekly demand of the population does not change throughout the study period. However, it does vary over the 168 h of a week. The base demand changes from node to node. The supply of the desired demand is not guaranteed, and deficit periods may occur. The number and location of leakages will not grow over the whole period. However, the intensity of leakage grows exponentially over time, if not repaired. That is, leakage coefficient values have to be updated at the beginning of each year. The recommended simulation time step with which the solutions presented by the participants will be analysed will be 1 hour.

On Leakages modelling

The following Figure shows the interpretation of the location of the leaks. The figure shows the case of a pipeline with two leaks located at distances (L1 and L2) from the initial node and whose leakage coefficients are k1 and k2. An excel file contains the information about the leakages initially present in the network. In the same file some rows are highlighted. The highlighted leakages must be added the other are already placed in the network file.



The single leakage can be assumed as concentrated in the closest node and can be simulated in EPANET as an emitter according to the law:

$$q = k \cdot p^{\alpha}$$

Where q is the leaked flow p is the pressure. Exponent α is considered equal to 1 and the emitter coefficient is specific for each leakage. Yearly, the unrepaired leaks will increase the emission coefficient k as follows:

$$k = k_0 \cdot e^{0.25\, w/260}$$

Where k_0 is the emitter coefficient at year 0, w is the number of weeks since year 0.

The value of coefficient k varies yearly, but not during the year, that is, k is updated at the beginning of the year and remain constant during the year. First update is at the end of year 1.

On well pumping

The dynamic level of each of the wells is assumed not to vary throughout the simulation.
The maximum operating flow rate of any pump shall never exceed the design flow rate of the pump (Q_0) by more than 50%. That is, the maximum flow that a pump can deliver is $1.5Q_0$. The pumps can operate in continuous mode or stop at certain times. The run/stop status of these pumps shall be determined through simple controls. Pumps could also be replaced by more powerful pumps, but the maximum flow rate that can be drawn from each well is limited, see table above.
Two additional elements can be added to each pump: a valve to control the flow rate, and a frequency inverter to vary the pump rotational speed. Any type of valve can be installed at the outlet of the pumps to limit the flow rate extracted from the well. Each of these valves will have an associated cost. Frequency inverters used to convert pumps into Variable Speed Pumps (VSPs) also have an associated cost, given as a function of the pump's power when operating at BEP (Q_0).

On monitoring system

Monitoring system is composed by flow meters and pressure transducers. Flow meters should be installed at the water source of the network to verify the MFR relative to the natural spring and the wells. Moreover, a flow meter is required each time a control is based on the flow rate in a link or when a part of the network is connected to another through a single pipe. Pressure transducers must be installed starting from the most critical nodes, i.e. those showing the minimum pressure in the network.

Performance indicators

In the following the suggested indicators to evaluate the performances of the network are defined. Indicators are based on the whole period of project development: i.e. 5+1 years.

- Indicator I_1: proportion of the number of effective hours a subscriber is served

Indicator I_1 reflects the proportion of the number of effective hours that a subscriber has service available over the hours in the 5+1 years.

$$I_1 = \frac{number\ of\ hours\ with\ service}{users \cdot total\ number\ of\ hours} = \frac{\sum_{j=1}^{6}\sum_{i=1}^{N} n_{i,j}}{N \cdot 24 \cdot 365 \cdot 6}$$

Where N is the number of users $n_{i,j}$ is the total number of hours per year the node i (node or user) has service (i.e. $P_i > P_0$) during year j. If $I_1 = 1$ every user is served at each time.

- Indicator I_2: proportion of subscribers with continuous service
  The second indicator reflects the proportion of users that has continuous service over the 6 years

$$I_2 = \frac{user\ with\ continuous\ service\ all\ 6\ years}{users\ \cdot years} = \frac{\sum_{j=1}^{6}\sum_{i=1}^{N} w_{i,j}}{N \cdot 6}$$

Where $w_{i,j}$ is 1 if user i has had continuous service ($p_{h,i,j}$> p_0) in year j, and 0 otherwise. Its value also ranges between 0 and 1.

- Indicator I_3: volume of water leakage
  The third indicator I_3 reflects the total volume of water leaked from the network after 6 years, referred to the total volume of water supplied, and is expressed as:

$$I_3 = \frac{water\ lost\ at\ the\ end\ of\ 6\ years}{water\ supplied} = \frac{\sum_{j=1}^{6}\sum_{l=1}^{Lj} V_{l,j}}{\sum_{j=1}^{6}\sum_{s=1}^{Sj} V_{s,j}}$$

Where $V_{l,j}$ is the volume lost by leakage l in year j, Lj is the number of active leakages in the same year, $V_{s,j}$ is the volume supplied by source s in year j, and Sj is the number of active sources in year j. Its value also ranges between 0 and 1. A value of 0 would mean no leakage after the first year's actions, while a value of 1 would mean that all the flow supplied is lost, with no water being received by the users during the whole period. Calculated for the single year this index is equal to the $M1_b$ defined by ARERA.

- Indicator I_4: proportion of volume of water supplied to users
  The fourth indicator I_4 is related to the previous one, but measures the volume of water required by subscribers that could not be supplied after 6 years. It is expressed as:

$$I_4 = \frac{water\ supplied\ to\ users\ in\ 6\ years}{water\ demanded\ by\ users\ in\ 6\ years} = \frac{\sum_{j=1}^{6}\sum_{i=1}^{N} V_{i,j}^{s}}{\sum_{j=1}^{6}\sum_{i=1}^{N} V_{i,j}^{d}}$$

where $V_{i,j}^{s}$ is the volume actually supplied to user i during year j, and $V_{i,j}^{d}$ is the volume demanded by user i during year j, and N is the total number of users (or nodes with demand). Its value also ranges between 0 and 1. A value of 0 would mean that no demand would be satisfied and a value of 1 would mean that all demands would be satisfied after the first year's actions. Let us note that all demands can be satisfied, but with a high volume of leakage in the network, which would also be unsatisfactory. Thus, indicator I_3 is complementary to I_4.

- Indicator I_5: level of pressures at consumption nodes

The fifth indicator I_5 measures the level of pressures available at the consumption nodes over the rehabilitation period, which is another way of reflecting the effectiveness of the measures taken. This level of effectiveness of the pressure supply is measured with respect to the reference pressure p_{ref} defined by the local laws. Mathematically the definition of the I_5 indicator can be expressed as:

$$I_5 = \frac{level\ of\ pressure\ at\ users}{hours \cdot reference\ pressure} = \frac{\sum_{j=1}^{6}\sum_{h=1}^{168}\sum_{i=1}^{N} \max\left(0, \min\left(p_{i,h,j}, p_{ref}\right)\right)}{168 \cdot N \cdot 6 \cdot p_{ref}}$$

Where $p_{i,h,j}$ is the pressure at node i and hour h of year j, expressed in m. Only nodes i with demand are considered, whose total number is N. Moreover, 168 are the hours of a week, since weeks are repetitive within the same year (52 weeks). In order to prevent the nodes with high pressures from distorting the mean pressure values; in the cases where the value of $p_{i,h,j}$ is higher than p_{ref}, the value of $p_{i,h,j}$ in equation shall be taken as p_{ref}.
The value of I_5 will range from 0 to a highest value of 1 when the average pressures in all nodes are above p_{ref}.

- Indicator I_6: percentage of users supplied continuously
  The sixth indicator I_6 determines the percentage of users who can be supplied on a continuous basis. This requires the pressure at the node to be greater than pf at all times. It is defined as:

$$I_6 = \frac{hours\ with\ pressure\ above\ limit}{users\ \cdot years} = \frac{\sum_{j=1}^{6}\sum_{i=1}^{N} \delta_{i,j}}{6 \cdot N}$$

Where $\delta_{i,j}$ is 1 if at node i $p_{h,i,j} > p_f$ for h = 1 ... 168, i.e. for all the hours of the week, and therefore of year j, is satisfied. Otherwise, it will be 0. Note that this condition can be met only from a certain year onwards and is more restrictive than the continuous supply condition reflected by I_2, where no minimum pressure limits are set, and less restrictive than the minimum pressure requirement p_{ref} reflected by I_5.

- Indicator I_7: Leakage per kilometre of network
  The seventh indicator I_7 determines the leakage entity expressed as a loss per kilometre of network:

$$I_7 = average\ of\ leakage\ per\ kilometre = \frac{\sum_{j=1}^{6}\left(\left(\sum_{l=1}^{Lj} V_{l,j}\right)/L_j\right)}{6}$$

whereL_j is the total length of the network at year j. Accounted for the single year this index is equal to the $M1_a$ defined by ARERA.

- Indicator I_8: specific energy consumption of pumps in operation over the whole period
  The eighth indicator I_8 takes into account the total energy consumption of the pumps in operation over the whole period. It is determined as:

$$I_8 = Specific\ energy\ consumed\ by\ pumps = \frac{\sum_{j=1}^{6}\sum_{p=1}^{P} E_{p,j}}{\sum_{j=1}^{6}\sum_{i=1}^{N} V_{i,j}^{s}}$$

where $E_{p,j}$ is the energy consumption of pump p over year j, expressed in kWh, and P is the total number of pumps in the network, and $V_{i,j}^{s}$ is the volume actually supplied to user i during year j.

- Indicator I_9: level of equity in supply

The last indicator I_9 reflects the level of equity in water supply to different subscribers. For this purpose it is proposed to use the indicator proposed by Gottipati and Nanduri (2014), which is expressed as:

$$I_9 = 1 - \frac{Average\ deviation}{Average\ supply\ ratio} = 1 - \frac{ADEV}{ASR}$$

$$SR_{i,j} = Supply\ ratio = \frac{V^s_{i,j}}{V^d_{i,j}}$$

$$ASR = average\ supply\ ratio = \frac{\sum_{j=1}^{6}\sum_{i=1}^{N} SR_{i,j}}{6 \cdot N}$$

$$ADEV = average\ deviation = \frac{\sum_{j=1}^{6}\sum_{i=1}^{N}\left|SR_{i,j} - ASR\right|}{6 \cdot N}$$

where $V^s_{i,j}$ is the volume actually supplied to user i during year j, $V^d_{i,j}$ is the volume demanded by the same subscriber in year j, and N is the total number of users (or nodes with demand). If all users receive the demanded volume, then ASR = 1, taking a value less than 1 when the network is deficient. Note that the definition of ASR is similar to that of the I_4 indicator, although not exactly the same. But if the ratio is the same for all users, then ADEV = 0 and I_9 = 1, which would be the ideal value. Since the average deviation cannot exceed the mean value, the minimum value of I_9 will be 0.

- Indicator I_{10}: level of digitalization of the network
  The last indicator I_{10} consider the monitoring level present in the network. It is defined as

$$I_{10} = \frac{\sum_{y=1}^{6} n_{sensor,y}}{Lnet}$$

Where n_s is the number of flow meters and pressure transducers installed and $Lnet$ is the total length of the network (about 235km).

Cost estimation

- Repairing leaks

$$C_{leak} = C_{det} + C_{repair}$$

Where C_{leak} is the total cost of the intervention, C_{det} is the cost of finding the leak and C_{rep} is the cost for the repairing. The components C_{det} and C_{repair} are calculated as follows:

$$C_{repair} = [94 - 0.3 \cdot D(mm) + 0.01 \cdot D(mm)^2] \cdot [1.5 + 0.11 \cdot log_{10}(k)]$$
$$C_{det} = 2400 \cdot e^{-28k}$$

Although the distribution of the leaks and their magnitude are provided in the starting data, it is assumed that the manager does not know them a priori, having a detection cost that is decreasing with the magnitude of the leak, and a repair cost that is increasing with the magnitude of the leak.

- Replacing pipes

$$C_{rep} = A_{rp} + B_{rp} \cdot D + C_{rp} \cdot D^2$$

Where C_{rep} is the replacing cost in €/m and D is the diameter of the pipe in m. The values of the cost function A_{rp}, $B_{rp}$and C_{rp}have been obtained by regressions from the pipe installation cost data: (A_{rp}= 13; B_{rp}= 29; C_{rp}= 1200). The inside diameters of the pipelines that can be installed to replace the existing ones are shown in the following Table. All new pipes to be installed shall have a Hazen-Williams coefficient (roughness) value of 120.

D (mm)	32	50	63	75	100	125	150	200	250
C_{rep} (€/m)	15.16	17.45	19.59	21.93	27.9	35.38	44.35	66.8	95.25
D (mm)		300	350	400	450	500	600	700	800
C_{rep} (€/m)		129.7	170.15	216.6	269.05	327.5	462.4	621.3	804.2

- Installing valves

$$C_{valve} = A_v D^{B_v}$$

where C_{valve} is the cost of installing a new valve in €/unit, *D* is the diameter of the valve in m and A_v and B_v are characteristic coefficients of the cost curve that depend on the type of valve (Following table)

Valve Type	*Av*	*Bv*
Isolation	99000	2.16
TCV	99000	2.16
PRV	260000	2.1
PSV	265000	2.1
FCV	275000	2.1

- Replacing pumps
The cost of installing a pump in a well can be divided in two different terms: the cost of extracting the installed pump (C_{ex}) and the cost of installing the new pump (C_{np}).

$$C_{pump} = C_{ex} + C_{np}$$

The cost of removing the installed pump and installing a new pump is calculated as a function of the depth at which the pump is located. This depth is the difference between the water level in the well and the level at the point immediately downstream of the pump. This cost is estimated at 500€ per meter of difference the elevation of this two points (water level and pump outlet). In the case of installing a pump that does not draw from a well, this cost will not be taken into account.
The installation cost of the new pump is calculated from the power (P_{BEP}) in the BEP

$$C_{np} = 1475 \cdot P_{BEP}^{0.525}$$

where C_{np} is the cost of installing a new pump and P_{BEP} is the power at the BEP of the installed pump in kW.

- Installing inverters
The cost associated with the installation of a frequency inverter depends directly on the power of the pump at its BEP. The cost including the installation of the inverter and the electrical adaptation of the system (C_{inv}) is given by the expression

$$C_{inv} = 1350 + 235 \cdot P_{BEP} - 1.2 \cdot P_{BEP}^2$$

where C_{inv} is the cost of installing the inverter and P_{BEP} is the power at the BEP of the installed pump in kW.
Once the frequency inverter has been installed, the pump can be adjusted to run at speeds different from the rated speed. In no case may a pump operate at speeds higher than the rated speed

- Installing SCADA system
The implementation of the scada system has two cost components:

$$C_{scada} = C_{scada,i} + C_{scada,c}$$

Where $C_{scada,i}$ is the cost of installation to be considered one time in the project and $C_{scada,c}$ is the cost of connection of each instrument to the SCADA system.

$$C_{scada,i} = 60'000 \qquad C_{scada,c} = 2'000 \cdot n_{ic}$$

Where n_{ic} is the number of connected instruments to the scada system. Each time a new instrument is installed and connected to the main scada the connection cost $C_{scada,c}$ must be considered.

- Installing instrumentation

$$C_{fm} = 1553{,}8 \cdot e^{0{,}0023D(mm)} + 1000 \qquad C_{pt} = 1000$$

Where C_{fm} is the cost of purchase and installation for a new flowmeter and C_{pt} is the cost of purchase and installation for a pressure transducer.

- Installing new adduction pipelines

$$C_{add} = L \cdot 0.5D^{1.18}$$

Where C_{add} is the cost of purchase and installation in field of a new pipeline, the cost comprehends all the necessary work. D is the diameter of the new pipeline in mm.

- Increasing the volume of the tanks

$$C_{tank} = 2000 + 250\Delta V$$

Where C_{tank} is the cost of increasing the capacity of the tank in € and ΔV is the increase in volume, in m^3

Software

Epanet is available for download at (https://www.epa.gov/water-research/epanet). It will be used for the modelling of drinking water distribution systems. It is an open-source widely used throughout the world modelling software. Today, engineers and consultants use EPANET to design and size new water infrastructure, retrofit existing aging infrastructure, optimize operations of tanks and pumps, reduce energy usage, investigate water quality problems, and prepare for emergencies.
Matlab will be used as folding software, Epanet can be used through Matlab commands to simplify the management of the simulations and of the results.
Epanet can be downloaded here:
https://www.epa.gov/water-research/epanet
The Matlab toolkit can be downloaded here:
https://github.com/OpenWaterAnalytics/EPANET-Matlab-Toolkit

Assignments

1) Define the operation at year zero, without investments (only operating on existing devices pumps and valves)
2) Define an investment program of 5 years to improve the performances of the network respecting all the restrictions. A monitoring system must be created at least to monitor flow rates from all the water sources and to monitor pressures in the most critical nodes. Each time a control is based on a measure an instrument must be installed to do the measurement.
   Performances must be evaluated through the indicators proposed.
   For each year of investment plus year 0 must be created a corresponding .inp file.
3) Create a buy list for the devices that must be purchased from the suppliers (Endress+Hauser (instruments) KSB (Pumps)).
4) Make a presentation of your investment plan.