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Numerical tool for hydraulic modelling – An educational approach

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Abstract

The scientific research devoted to modelling and simulation of water supply systems is, most of the times, dependent on the use of computer simulation programmes that requires a previous understanding on each specific programme particularities. At the same time, such programmes do not demonstrate to be open, with unconcealed data, simple and intuitive enough for teaching practices in the field of hydraulics. Therefore, other educational tools or approach should be taken. A numerical educative tool, developed in an Excel spreadsheet for the modelling and simulation of water networks operations is presented in this article. Intuitive and easy to adapt to several situations, the developed Excel-based tool presents large possibilities, not only for decision-support concerning the application of certain efficiency measures but also for pedagogical activities, allowing to understand with detail and immediately the effect of any control and/or design change in the daily operation of a water network, and hence in the associated daily energetic costs. Additionally, a number of analyses concerning the convenience of applying efficiency measures in such systems (namely the use of variable-speed pumps) is suggested and performed resorting to the developed tool. The developed tool has been applied in Fluid Mechanics classes with large success, demonstrating great potential for educational purposes.

Keywords

Hydraulic education, fluid mechanics, pedagogy, hydraulic efficiency, modelling, numerical tool, water supply systems

Introduction

The worldwide concerns with economic and environmental sustainability lead to the increase of the importance given to the detailed understanding on the operation

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of certain systems in order to control them efficiently (on both energetic and economic ways). This is the case of the water supply systems that deal with large amounts of energy usually responsible for a large portion of the total costs associated to their operation. The importance of energy and environment sustainability, in addition to the efficiency concerns, is a vital and imperative topic in all science and engineering courses, in particular to hydraulic subjects, and its meaning should be assimilated by all students.

Since the water networks are very complex systems, understanding some aspects in their operation and, at the same time, dealing with a large number of elements such as multiple pumps, valves and tanks can become a difficult task. That is why workers and researchers in the water field often rely on computer programmes for supporting the management, operation and analysis of water systems.[1] In fact, the use of modelling computer programmes for the analysis of water supply networks attending to the networks hydraulic behaviour and also to their operational efficiency is the most common among researchers and students of hydraulic engineering.

Given the high importance of laboratory assignments in classes (see Figure 1(a)), the numerical laboratory work can be an excellent replacement of experimental laboratory classes with several advantages recognized by the students (Figure 1(b)). In the specific field of hydraulics and water networks, it was verified that the use of hydraulic simulators contributes significantly to the understanding acquisition of the contents of the subject.

However, such programmes are generally black-box solutions and, therefore, do not provide open and intuitive solutions of the network behaviour under distinct operational controls imposed by the user. At the same time, explaining some

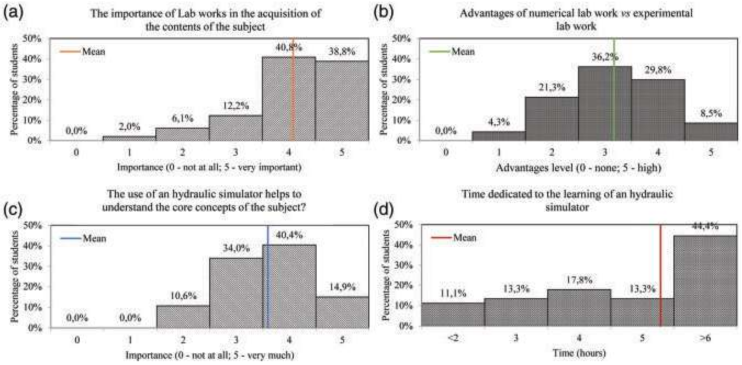


Figure 1. Results of a survey made to 180 students of the Fluid Mechanics course: (a) The importance of practical laboratory works in the acquisition of the contents of the course; (b) advantages of numerical *vs* experimental laboratory work; (c) the usefulness of an hydraulic simulator to the understanding of the core concepts of the subject; (d) time dedicated to the learning of an hydraulic simulator.

particular hydraulic concepts in such black-box programmes can be also a difficult task when teaching hydraulics. Additionally, the time required to a student to learn a general hydraulic simulator can be incompatible to the available time. Generally, as shown in Figure 1(d), a student needs an average time of 5.3 h to learn using such a program. Even considering open-source software, several codes are not usually intuitive for students and certainly not accessible to demonstrate hydraulics applications during lessons. Consequently, the modelling and simulation computer programmes commonly used in industry are not indicated for pedagogic purposes.

Using modelling and simulation computer programmes for the analysis of certain efficiency measures and advantages/disadvantages of such measures in specific water systems can also present difficulties due to limitations imposed, for instance, by the graphical user interface (GUI) of each programme or even by limitations concerning some optional parameters (system parameters or modelling conditions, for instance) that are predefined by the software developer and cannot be easily (or cannot even be) modified by the user.

A survey was conducted in the subject of Fluid Mechanics, where a hydraulic simulator (EPANET 2.0) was used in the numerical laboratory classes. In these classes, with a total number of 113 students, the students pointed out that the definition of the initial values, such as the hydraulic day patterns, was the most difficult step in the work, along with finding the best operational solution (see results in Figure 2). However, this step should not be in this rank of difficulties. It should be straightforward considering that it consists in the introduction of a couple of numbers in a specific window (GUI) of the program. This show that, even with a GUI, the program is not intuitive and particularly addressed for students.

In this context, the present work proposes the use of a well-known Excel[a] worksheet for an intuitive, and hence educative, demonstration on how to model and simulate water distribution networks. Following a similar methodology to the

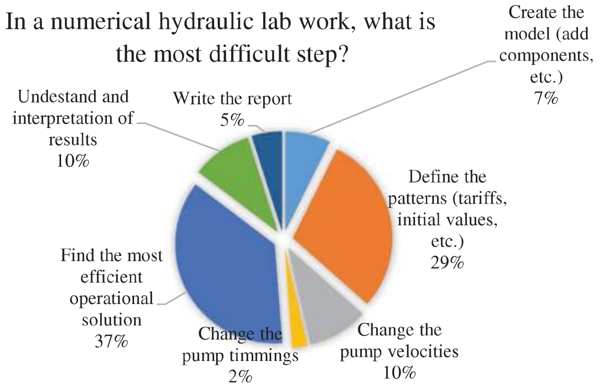


Figure 2. The most difficult work-stage in the laboratory assignment using an hydraulic simulator pointed out by the students.

hydraulic simulator EPANET, the developed Excel-based tool provides a model of a single-pumped water network and simulates its operation during a period of 24 h. Such tool allows the user to change specific network characteristics or even operational parameters, such as the pump speed and its operating time, and automatically obtain the simulation results for each hour of the simulated day and for all the elements of the network, considering the corresponding changes.

Taking advantage of the developed tool, a number of studies concerning several issues commonly discussed in the scope of the efficiency achievement in water supply systems[2] were performed and discussed in this article. The authors suggest the execution of these analyses with the proposed educational tool for Hydraulic and Fluid mechanics classes. For advanced classes, the proposed numerical tool can be even used to find optimum solutions using optimization strategies. In summary, a list of the modelling options analysed in this work in order to quantify their effects on the energetic and economic savings computation is given as:

- Types of efficiency – pumps with constant efficiency or with an efficiency curve are analysed and compared;
- Types of pumps – using a pump with variable speed instead of constant speed;
- Operating time-steps definition – distinct operating times for the pump operation instead of the common fixed 1-h operating time-steps are used when modelling a network operation. A comparison is studied;
- Influence of multiple head loss curves – testing the use of variable-speed pumps in systems with distinct head loss curves.

Modelling an educational hydraulic case-study

For educational purposes, a simple and intuitive hydraulic case-study should be used. Therefore, no more than one hydraulic element per type should be used. Although the authors have tested different case-studies in class, the following case-study turned out to be the most pedagogically successful one.

Two distinct modelling tools can be used for the hydraulic and energetic analysis of the case-study network described in the following section 2.1: (a) a generic hydraulic simulator, such as, for example, EPANET 2.0 and (b) an intuitive and dedicated numerical tool developed particularly for the case-study. Considering that the main purpose of the numerical tool is educational, the authors suggest the second approach. Therefore, an Excel worksheet[b] was developed specifically for the corresponding network.

An educational tool as the one developed and presented in this work has several advantages. The most important are the following:

1. The tool is implemented using an Excel worksheet. This kind of software is used by almost all computer users in the world. At the same time, other tools

commonly require specific knowledge, which implies additional efforts to the user and may not be practical, for instance, to be used in classes.

2. The tool provides, in a unique table, the hourly information for the characteristics of all the network elements including flows, head losses, consumptions, efficiency, power, energy, costs, levels and volumes, allowing the user to analyse their evolution during the simulated day.
3. It is possible to modify any parameter of the pump operation (operating time and relative speed) and automatically obtain the behaviour of the system resulting from the operation under the new conditions, both in table and graphical format.
4. It allows to change the characteristics of the network elements, such as dimensions, pump efficiency and/or characteristic curve, energy tariff, etc., and visualise the new system and pump curves as well as the resulting behaviour of the model during the simulation period.
5. If desired by the user, the method used for the prediction of the pump behaviour operating at distinct speeds can be replaced by others more adequate to a specific pump and/or system.
6. The tool reveals to be useful for decision making concerning the installation of a VFD in systems characterised by distinct head loss curves, since it provides the possible benefits from such installation.

Description of the case-study network

The presented study network (see Figure 3(a)) is composed of a water source, a storage reservoir (or tank) that supplies the point of consumption represented by node N2 (with an associated consumption pattern) and one pump responsible for pumping the water between the source and the tank.

The elevations of the node N1, the tank and node N2 are, respectively, 10, 100 and 90 m and the total head of the water source is 10 m. The tank has a diameter of

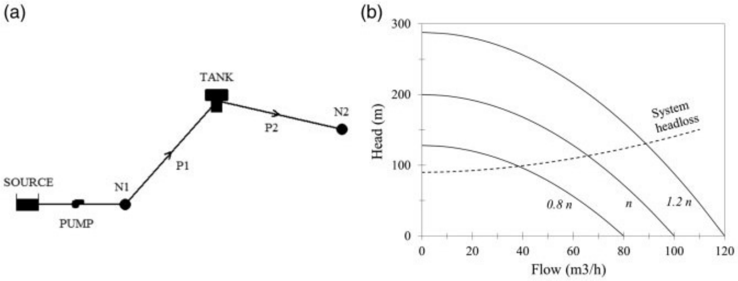


Figure 3. (a) Representation of the case-study network used in this work and (b) system head loss curve and pump characteristic curves (at nominal speed, *n*, and at lower and higher relative speeds, 0.8*n* and 1.2*n*, respectively) of the case-study network.

5 m and their minimum and maximum levels of operation are 2 and 20 m, respectively. The pump characteristic head curve as well as the corresponding curves for the pump at a lower and a higher relative speeds (80% and 120% of the nominal speed) and the curve of the network pipes head loss are provided in Figure 3(b). The base demand of node N2 is 10 m^3/h and the associated pattern demand is provided in Figure 4, which also includes the pattern for the energy price variation during a representative day.

The pipe that links node N1 to the tank (pipe P1) is characterised by a length of 2000 m, a diameter of 200 mm and a roughness coefficient of 50. The pipe that links the tank to node N2 (pipe P2) presents exactly the same dimensions and also a roughness coefficient of 50 is considered for the Hazen-Williams head loss calculation. In order to ignore minor head losses in both pipes, the minor head loss coefficient was set to zero.

Development of an hydraulic educational tool

The characteristics for the modelling analysis of each element of the pipe network can be seen in Table 1.

Similarly to the general hydraulic simulators, the flow continuity and head loss equations that characterise the hydraulic state of the pipe network for each point at

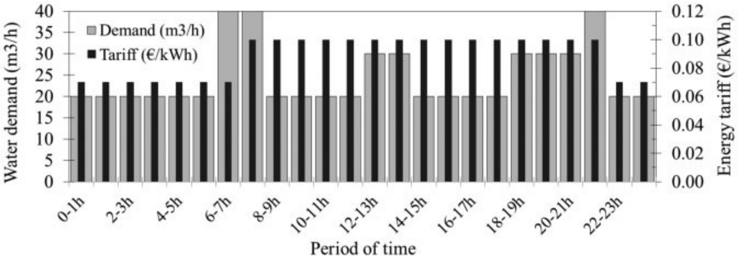


Figure 4. Water demand pattern associated to node N2 of the case-study network and the pattern of energy price (tariff) considered for the operational energy costs computation.

Table 1. Characteristics of each element enclosed for modelling the case-study network.

Pump	Pipe P1	Tank	Pipe P2	Demand node
Speed/status, operating time, power, efficiency, energy, delivered head and flow, demand charge, total cost	Head loss, flow	Actual level, volume, min level, max level	Head loss, flow	Base demand, demand pattern, demand, pressure

each defined time period in which the simulation time is divided must be solved by the proposed educational tool. Consequently, the hydraulic continuity equation, the equations that define head-losses (here, the Hazen-Williams formula), pump characteristic curves, affinity laws, power and efficiency equations, network operational cost equation must be used. These equations can be seen in other publications.[3–6]

Figure 5 shows an implementation of all previously mentioned data for the case-study network using Excel providing examples of results for the characteristics enumerated in Table 1 for 24 consecutive time periods of 1 h. This figure demonstrates how simple is to change a network characteristic, such as the system head loss curve, or even to change an operational parameter, such as the pump speed, and automatically obtain the results for the behaviour of each network element for each time period of the simulation. This kind of results presentation also allows the user to directly and immediately obtain the graphical representation of the desired characteristics of one or more elements of the network.

Excel implementation

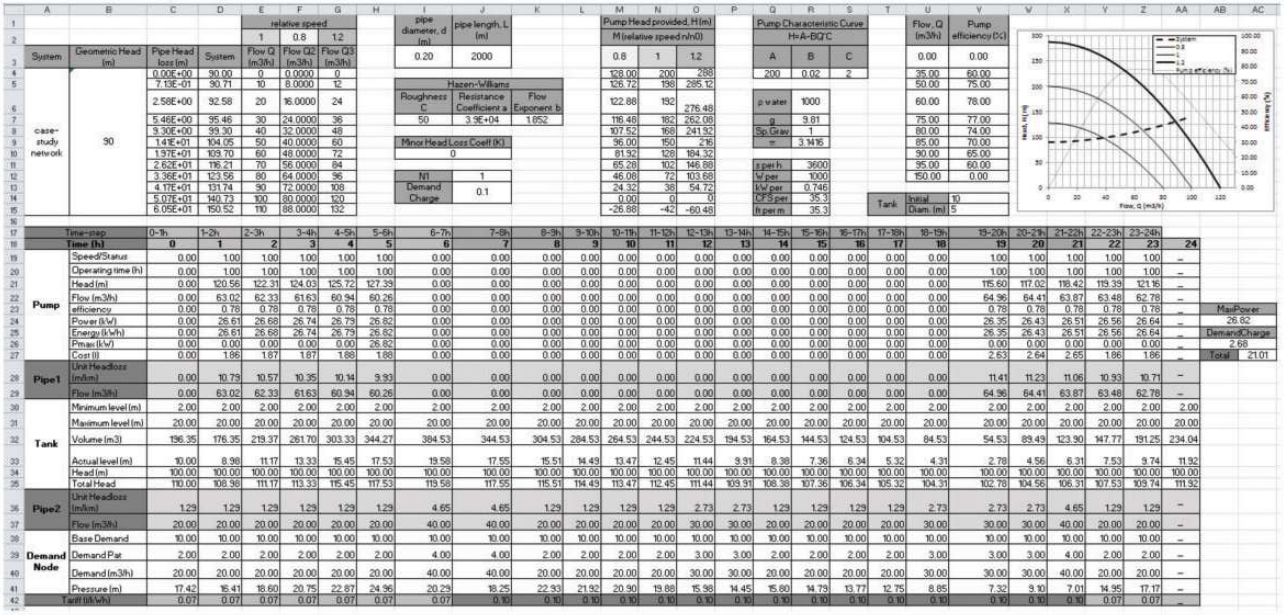
As can be observed in Figure 5, the characteristics associated to the pump are represented in rows 19 to 27, followed by the characteristics of pipe P1 in rows 28 and 29. From rows 30 to 35, the limits of tank water levels and the daily variation are presented. Rows 36 and 37 contain the pipe P2 characteristics and, finally, the demand and pressure of node N2 and the pattern of the energy price are provided in the last rows (36 to 42).

Figure 6 specifies the formulae used in each cell of the developed tool for the first 2 h of the simulated day (columns C and D). Each following hour uses exactly the same formulae presented for the second time-step (1–2 h).

Before starting to fill the worksheet with the necessary formulae, the user must insert the initial speed and time pattern for the pump operation (rows 19 and 20). Other system operational parameters defined by the user should also be initially inserted: the pattern for the energy price variation (row 42), the water demand pattern and the corresponding base demand of node N2 (rows 38 and 39), the tank elevation (row 34) as well as its minimum and maximum levels (rows 30 and 31, respectively).

Specific characteristics of the network elements must also be initially defined by the user: (a) the pump characteristic curve coefficients (cells Q4, R4 and S4), (b) the pump efficiency curve points (U1 to V12), (c) the tank initial level (V14) and diameter (V15), (d) the system static head, i.e. the difference in elevation between the tank and the source (B4) and, finally, (e) the pipes characteristics, such as dimensions (I3 and J3) and the coefficients for the head loss calculation.

For both pipes P1 and P2, considering the length of each pipe and the equation for the head losses calculation, the unit head loss in m/km (rows 28 and 36) can be obtained. The continuity equation for the flow is applied in row 37 in order to obtain the flow of pipe P2.



				relative speed		
				1	0.8	1.2
System	Geometric Head (m)	Pipe Head loss (m)	System	Flow Q (m3/h)	Flow Q2 (m3/h)	Flow Q3 (m3/h)
case-study network	90	0.00E+00	90.00	0	0.0000	0
		7.13E-01	90.71	10	8.0000	12
		2.58E+00	92.58	20	16.0000	24
		5.46E+00	95.46	30	24.0000	36
		9.30E+00	99.30	40	32.0000	48
		1.41E+01	104.05	50	40.0000	60
		1.97E+01	109.70	60	48.0000	72
		2.62E+01	116.21	70	56.0000	84
		3.36E+01	123.56	80	64.0000	96
		4.17E+01	131.74	90	72.0000	108
		5.07E+01	140.73	100	80.0000	120
		6.05E+01	150.52	110	88.0000	132

pipe diameter, d (m)	pipe length, L (m)
0.20	2000

Hazen-Williams		
Roughness C	Resistance Coefficient a	Flow Exponent b
50	3.9E+04	1.852

Minor Head Loss Coeff (K)
0

N1	1
Demand Charge	0.1

Pump Head provided, H (m)		
M (relative speed n/n0)		
0.8	1	1.2
128.00	200	288
126.72	198	285.12
122.88	192	276.48
116.48	182	262.08
107.52	168	241.92
96.00	150	216
81.92	128	184.32
65.28	102	146.88
46.08	72	103.68
24.32	38	54.72
0.00	0	0
-26.88	-42	-60.48

Pump Characteristic Curve		
H=A-BQ^C		
A	B	C
200	0.02	2

ρ water	1000
g	9.81
Sp.Grav	1
π	3.1416

s per h	3600
W per	1000
kW per	0.746
CFS per	35.3
ft per m	35.3

Flow, Q (m3/h)	Pump efficiency (%)
0.00	0.00
35.00	60.00
50.00	75.00
60.00	78.00
75.00	77.00
80.00	74.00
85.00	70.00
90.00	65.00
95.00	60.00
150.00	0.00

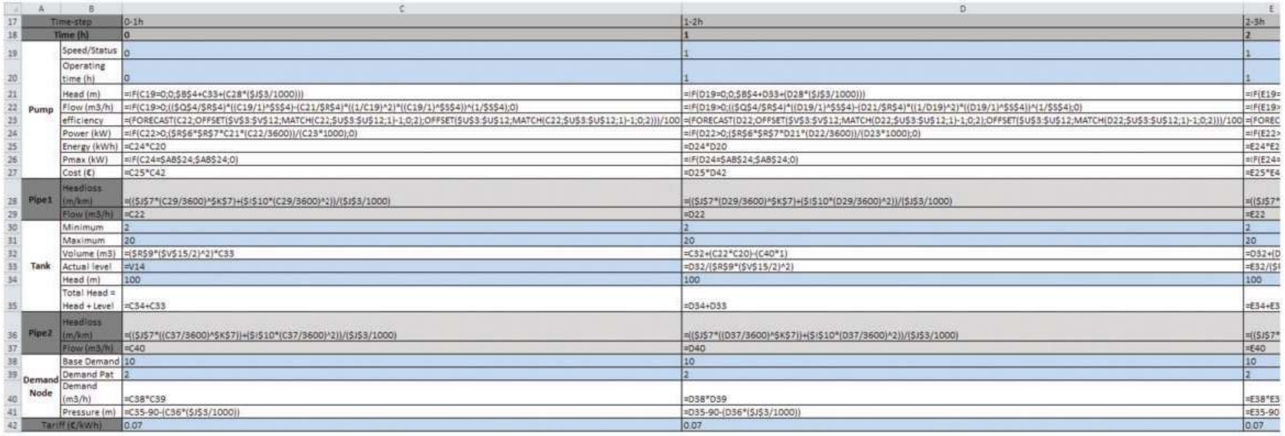
Tank	Initial	10
	Diam. (m)	5

Time-step		0-1h	1-2h	2-3h	3-4h	4-5h	5-6h	6-7h	7-8h	8-9h	9-10h	10-11h	11-12h	12-13h
Time (h)		0	1	2	3	4	5	6	7	8	9	10	11	12
Pump	Speed/Status	0.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Operating time (h)	0.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Head (m)	0.00	120.56	122.31	124.03	125.72	127.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Flow (m3/h)	0.00	63.02	62.33	61.63	60.94	60.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	efficiency	0.00	0.78	0.78	0.78	0.78	0.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Power (kW)	0.00	26.61	26.68	26.74	26.79	26.82	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Energy (kWh)	0.00	26.61	26.68	26.74	26.79	26.82	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Pmax (kW)	0.00	0.00	0.00	0.00	0.00	26.82	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Cost (€)	0.00	1.86	1.87	1.87	1.88	1.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pipe1	Unit Headloss (m/km)	0.00	10.79	10.57	10.35	10.14	9.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Flow (m3/h)	0.00	63.02	62.33	61.63	60.94	60.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tank	Minimum level (m)	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Maximum level (m)	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
	Volume (m3)	196.35	176.35	219.37	261.70	303.33	344.27	384.53	344.53	304.53	284.53	264.53	244.53	224.53
	Actual level (m)	10.00	8.98	11.17	13.33	15.45	17.53	19.58	17.55	15.51	14.49	13.47	12.45	11.44
	Head (m)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
	Total Head	110.00	108.98	111.17	113.33	115.45	117.53	119.58	117.55	115.51	114.49	113.47	112.45	111.44
Pipe2	Unit Headloss (m/km)	1.29	1.29	1.29	1.29	1.29	1.29	4.65	4.65	1.29	1.29	1.29	1.29	2.73
	Flow (m3/h)	20.00	20.00	20.00	20.00	20.00	20.00	40.00	40.00	20.00	20.00	20.00	20.00	30.00
Demand Node	Base Demand	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
	Demand Pat	2.00	2.00	2.00	2.00	2.00	2.00	4.00	4.00	2.00	2.00	2.00	2.00	3.00
	Demand (m3/h)	20.00	20.00	20.00	20.00	20.00	20.00	40.00	40.00	20.00	20.00	20.00	20.00	30.00
	Pressure (m)	17.42	16.41	18.60	20.75	22.87	24.96	20.29	18.25	22.93	21.92	20.90	19.88	15.98
Tariff (€/kWh)		0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.10	0.10	0.10	0.10	0.10	0.10

Time-step		13-14h	14-15h	15-16h	16-17h	17-18h	18-19h	19-20h	20-21h	21-22h	22-23h	23-24h	
Time (h)		13	14	15	16	17	18	19	20	21	22	23	24
Pump	Speed/Status	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	–
	Operating time (h)	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	–
	Head (m)	0.00	0.00	0.00	0.00	0.00	0.00	115.60	117.02	118.42	119.39	121.16	–
	Flow (m3/h)	0.00	0.00	0.00	0.00	0.00	0.00	64.96	64.41	63.87	63.48	62.78	–
	efficiency	0.00	0.00	0.00	0.00	0.00	0.00	0.78	0.78	0.78	0.78	0.78	–
	Power (kW)	0.00	0.00	0.00	0.00	0.00	0.00	26.35	26.43	26.51	26.56	26.64	–
	Energy (kWh)	0.00	0.00	0.00	0.00	0.00	0.00	26.35	26.43	26.51	26.56	26.64	–
	Pmax (kW)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	–
	Cost (€)	0.00	0.00	0.00	0.00	0.00	0.00	2.63	2.64	2.65	1.86	1.86	–
Pipe1	Unit Headloss (m/km)	0.00	0.00	0.00	0.00	0.00	0.00	11.41	11.23	11.06	10.93	10.71	–
	Flow (m3/h)	0.00	0.00	0.00	0.00	0.00	0.00	64.96	64.41	63.87	63.48	62.78	–
Tank	Minimum level (m)	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Maximum level (m)	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
	Volume (m3)	194.53	164.53	144.53	124.53	104.53	84.53	54.53	89.49	123.90	147.77	191.25	234.04
	Actual level (m)	9.91	8.38	7.36	6.34	5.32	4.31	2.78	4.56	6.31	7.53	9.74	11.92
	Head (m)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
	Total Head	109.91	108.38	107.36	106.34	105.32	104.31	102.78	104.56	106.31	107.53	109.74	111.92
Pipe2	Unit Headloss (m/km)	2.73	1.29	1.29	1.29	1.29	2.73	2.73	2.73	4.65	1.29	1.29	–
	Flow (m3/h)	30.00	20.00	20.00	20.00	20.00	30.00	30.00	30.00	40.00	20.00	20.00	–
Demand Node	Base Demand	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	–
	Demand Pat	3.00	2.00	2.00	2.00	2.00	3.00	3.00	3.00	4.00	2.00	2.00	–
	Demand (m3/h)	30.00	20.00	20.00	20.00	20.00	30.00	30.00	30.00	40.00	20.00	20.00	–
	Pressure (m)	14.45	15.80	14.79	13.77	12.75	8.85	7.32	9.10	7.01	14.95	17.17	–
Tariff (€/kWh)		0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.07	0.07	–

MaxPower	
26.82	
DemandCharge	
2.68	
Total	21.01

Figure 5. Representation of part of the developed Excel-based tool, showing an example of values evolution, within a period of 24 h, for the case-study network characteristics.



	A	B	C	D	E
17	Time-step		0-1h	1-2h	2-3h
18	Time (h)		0	1	2
19	Pump	Speed/Status	0	1	1
20		Operating time (h)	0	1	1
21		Head (m)	=IF(C19=0;0;$B$4+C33+(C28*($J$3/1000)))	=IF(D19=0;0;$B$4+D33+(D28*($J$3/1000)))	=IF(E19=
22		Flow (m3/h)	=IF(C19>0;(($Q$4/$R$4)*((C19/1)^$S$4)-(C21/$R$4)*((1/C19)^2)*((C19/1)^$S$4))^(1/$S$4);0)	=IF(D19>0;(($Q$4/$R$4)*((D19/1)^$S$4)-(D21/$R$4)*((1/D19)^2)*((D19/1)^$S$4))^(1/$S$4);0)	=IF(E19>
23		efficiency	=(FORECAST(C22;OFFSET($V$3:$V$12;MATCH(C22;$U$3:$U$12;1)-1;0;2);OFFSET($U$3:$U$12;MATCH(C22;$U$3:$U$12;1)-1;0;2)))/100	=(FORECAST(D22;OFFSET($V$3:$V$12;MATCH(D22;$U$3:$U$12;1)-1;0;2);OFFSET($U$3:$U$12;MATCH(D22;$U$3:$U$12;1)-1;0;2)))/100	=(FOREC
24		Power (kW)	=IF(C22>0;($R$6*$R$7*C21*(C22/3600))/(C23*1000);0)	=IF(D22>0;($R$6*$R$7*D21*(D22/3600))/(D23*1000);0)	=IF(E22>
25		Energy (kWh)	=C24*C20	=D24*D20	=E24*E2
26		Pmax (kW)	=IF(C24=$AB$24;$AB$24;0)	=IF(D24=$AB$24;$AB$24;0)	=IF(E24=
27		Cost (€)	=C25*C42	=D25*D42	=E25*E4
28	Pipe1	Headloss (m/km)	=(($J$7*(C29/3600)^$K$7)+($I$10*(C29/3600)^2))/($J$3/1000)	=(($J$7*(D29/3600)^$K$7)+($I$10*(D29/3600)^2))/($J$3/1000)	=(($J$7*
29		Flow (m3/h)	=C22	=D22	=E22
30	Tank	Minimum	2	2	2
31		Maximum	20	20	20
32		Volume (m3)	=($R$9*($V$15/2)^2)*C33	=C32+(C22*C20)-(C40*1)	=D32+(D
33		Actual level	=V14	=D32/($R$9*($V$15/2)^2)	=E32/($
34		Head (m)	100	100	100
35		Total Head = Head + Level	=C34+C33	=D34+D33	=E34+E3
36	Pipe2	Headloss (m/km)	=(($J$7*((C37/3600)^$K$7))+($I$10*(C37/3600)^2))/($J$3/1000)	=(($J$7*((D37/3600)^$K$7))+($I$10*(D37/3600)^2))/($J$3/1000)	=(($J$7*
37		Flow (m3/h)	=C40	=D40	=E40
38	Demand Node	Base Demand	10	10	10
39		Demand Pat	2	2	2
40		Demand (m3/h)	=C38*C39	=D38*D39	=E38*E3
41		Pressure (m)	=C35-90-(C36*($J$3/1000))	=D35-90-(D36*($J$3/1000))	=E35-90
42	Tariff (€/kWh)		0.07	0.07	0.07

Figure 6. Detail of the developed Excel-based tool showing the formulae used in each cell for the first 2 h of the simulated day.

The pump flow rate at each time-step (row 22) is obtained by using the equation derived from the affinity laws written as a function of flow. Then, the head provided by the pump to the water is determined in row 21.

Concerning the tank water level, in the first hour of the simulation (cell C33), the initial level defined by the user is inserted and the initial volume of water (cell C32) is computed considering a cylindrical shape for the tank. In the following hours, the updated volume is computed.

The pump efficiency at each time-step is determined according to the formula presented in cell C23 of Figure 6, which corresponds to a linear interpolation from the table that provides the points of the pump efficiency curve. Then, after obtaining the pump efficiency, the power consumed by the pump (row 24) can be calculated and multiplying such value by the operating time, the energy consumption (row 25) is obtained. The cost at each step is computed considering the value of the energy price at the corresponding hour of the day (row 27) and then the total cost is given by the sum of all the steps (cell AC27 of Figure 5).

Extensions and other capabilities

Although not explored in this article, it is important to mention the capabilities of Microsoft Excel for solving optimisation problems. Thus, another advantage of modelling and simulating a water network using this Excel-based tool is the possibility of easily testing some optimisation techniques available in the Excel solver. This can be also an interesting and simple way to introduce the concept of water distribution networks optimisation in classes.

Using the *Solver* of Microsoft Excel, the user can simply select the cell containing the value to be minimised (the total cost, in this case, in cell AC27) and then select the cells corresponding to the optimisation variables, which can be (a) the pump speed, in row 19, (b) the operating time, in row 20, or (c) both. Finally, the user must define the constraints related to variables bounds, minimum and maximum tank water levels, value of the final level of water in tank or continuity constraint[c] and minimum nodal pressure. [AQ1]

Using the method selected by the user, the Excel solver will then search for the adequate variables to solve the general optimisation problem that can be mathematically defined by Coelho and Andrade-Campos[2]:

$$\begin{array}{lll} \text{min(or max)} & f(\mathbf{X}) & \\ \text{subject to} & g_m(\mathbf{X}) \leq 0, & m = 1, \ldots, M, \\ & h_l(\mathbf{X}) = 0, & l = 1, \ldots, L, \end{array} \tag{1}$$

where $\mathbf{X} = (x_1, \ldots, x_n)$ is the vector of n decision variables (pump speed and/or time values at each time-step); M and L are, respectively, the number of inequality and equality constraints that must be satisfied during the optimisation of the objective function f (minimisation of the total cost, in this particular case).

A number of approaches and works dealing with this thematic are discussed in a recently published review.[2]

Class exercises and analysis of results

The analyses proposed in this section start with simpler controls to more complex and more efficient ones. The order of this analysis was selected taken in account educational reasons.

The case-study network described in section is modelled for a simulation period of 1 day divided into time periods of 1 h (1-h time-steps). Figure 7 shows the patterns of the pump operation considered in the different analyses of the network, as well as the results of the water level in tank during all period of operation. A demand charge of $DC = 0.1$ is associated to the pump. Figure 8 provides the representation of the efficiency curve considered for the pump and also the pump operating points for each time period of the several simulations considering the controls represented by each of the pump pattern of Figure 7. It should be noted that all these results were also validated using the hydraulic simulator EPANET 2.0.

The analyses suggested are:

1. *Fixed time-step and constant pump speed – Initial modelling conditions*: for the first hydraulic simulation of the network operation, the time periods are considered fixed, meaning that the pump is only allowed to operate during the entire time-step (never less than 1 h). At the same time, only the nominal speed of pump is considered. As observed in Figure 7(a), the variation of the energy price during the day is taken into account and the pump is mainly operating during the lower electricity cost periods. Such operational conditions represent already an intuitive attempt to model the most efficient operation of the case-study network considering a pump with no variable speed.

Despite the pump is always operating at the same speed, it is possible to observe that the results for the operating points (also similar to the obtained with EPANET) are slightly deviated. This is caused by the variations of the water level in tank. When the water level is higher, the pump will need more energy to overcome the elevations difference and then, the corresponding operating point will be deviated to superior values of pumping head.

It should be noted that the tank water level in the end of the simulation period (at 24 h) is never allowed to be inferior to the initial level, i.e. never lower than the water level in the beginning of the simulation (at 0 h, in this case).

(a) Model considering constant efficiency: This solution considers a pump with a constant efficiency of 75%. The daily cost computed by the Excel-based tool has the value of 21.79 €.
(b) Model considering an efficiency curve: this model considers a variation of the pump efficiency with the pumped flow instead of a constant efficiency.

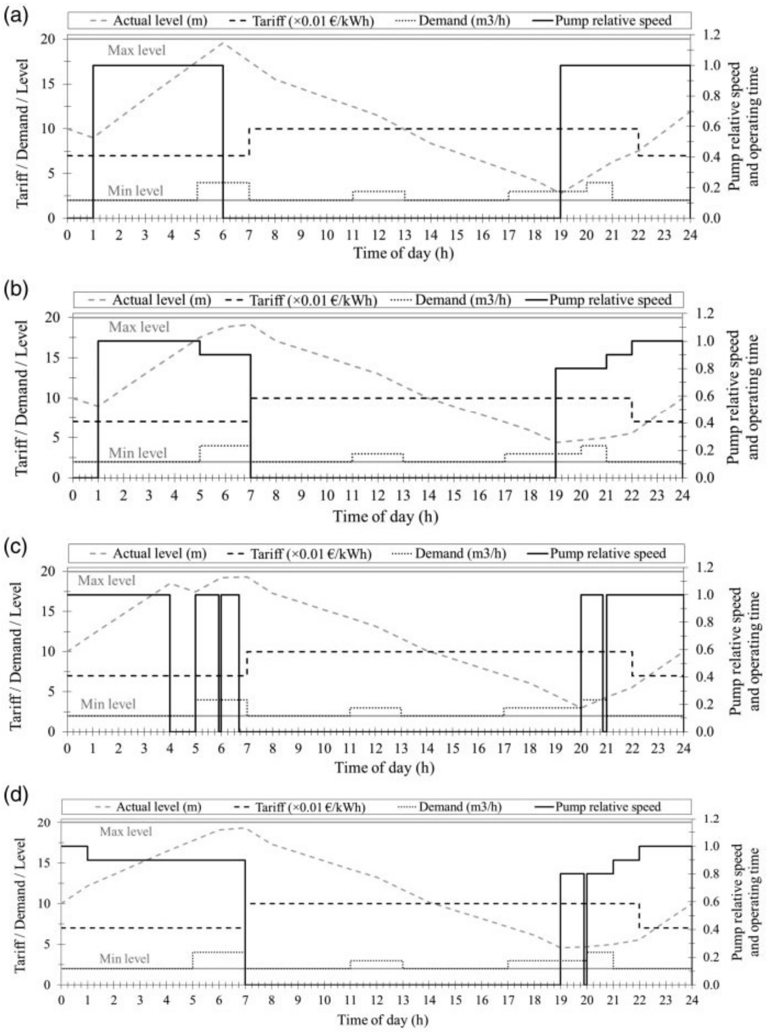


Figure 7. (a) Initial pattern considered for the operation of the pump of the case-study network and evolution of the water level in tank during the simulation period considering such pump controls. Comparison with patterns of both water demand and energy price (tariff). (b) Main characteristics of the case-study network model, during the 24-h simulation period, considering distinct speeds for pump. (c) Main characteristics of the case-study network model during the 24-h simulation period considering distinct operating times instead of the fixed 1 h. (d) Main characteristics of the case-study network model during the 24-h simulation period considering both distinct pump operating times instead of the fixed 1-h step and also distinct pump speeds.

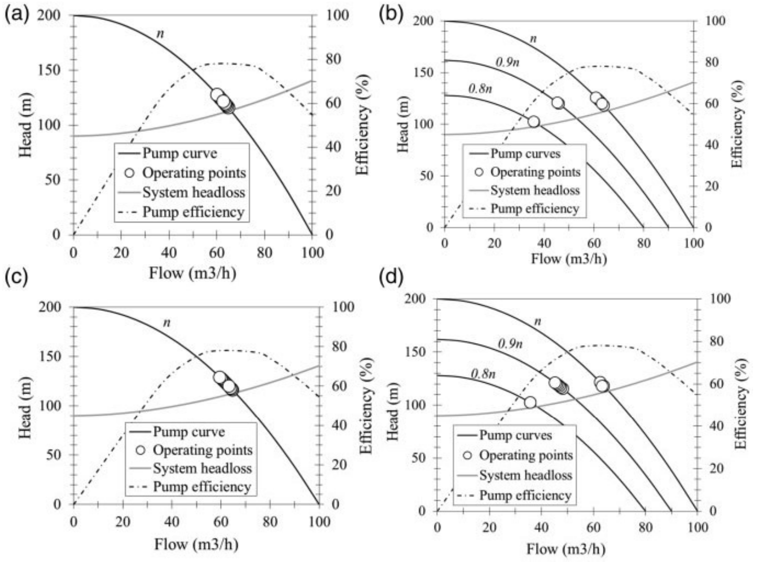


Figure 8. (a) Representation of (i) the efficiency curve and (ii) the pump operating points correspondent to the controls considered in the initial model of the case-study network. (b) Results of the pump operating points for the model considering distinct pump speeds. (c) Results of the pump operating points for the model considering distinct operating times instead of the fixed 1-h step. (d) Results of the pump operating points for the model considering a variable-speed pump with distinct operating times instead of the fixed 1-h step.

The considered pump efficiency curve is represented in Figure 8(a). Considering the same initial conditions for the network operation during the simulation period of 1 day, the average efficiency of the pump is 77.8%. The daily cost associated to the pump operation is 21.01 €, computed with the Excel-based tool. As expected, since the average pump efficiency is superior to the constant efficiency considered in the previous model, the computed daily cost is consequently inferior. Besides the difference between the computed costs when compared with the model using constant efficiency, the behaviour of the network, respecting the tank water levels and the pump operating points, follows the same pattern since the controls used for the pump (speed and operating time) are exactly the same.

2. *Modelling changes in pump speed:* At this analysis, the influence of using, for instance, a variable frequency drive (VFD) for changing the pump speed in order to reduce the operational costs is tested. Therefore, a different pattern for the pump operation, considering distinct speeds, is considered. The pump speed pattern considered for the model of this section is represented in Figure 7(b). The pump relative speed was reduced to 0.9 from 5 a.m. to 7 a.m. and from 9 p.m. to 10 p.m. From 7 p.m. to 9 p.m., the speed was reduced to 80% of the nominal (0.8).

Although Figure 7(b) shows a similar pattern of the tank water level evolution when compared with the initial model, improvements in the operational costs were obtained by using distinct pump speeds. Considering the described conditions and a constant pump efficiency of 75%, the daily operational cost of the case-study network obtained with the Excel-based tool is 19.12 €. When considering the pump efficiency curve, the operational cost of the case-study network has the value of 19.47 €. The average pump efficiency, in this case, is 73.2%.

Figure 8(b) shows the pump operating points at each distinct speed considered. Despite the pump is operating at certain time periods in efficiency conditions superior to 75%, in other periods, the pump operates at lower-efficiency points, resulting in an average efficiency inferior to 75%. It is also observed that the pump is not operating at the most efficient point (the point where the pump head curve intersects the system characteristic head loss curve) at 90% of the nominal speed. On the other hand, the use of the pump at lower speeds enable the pump to adapt to the demand variability and operate at smaller flow and head values which, in turn, results in a reduction of the power consumption. The results obtained in this modelling case demonstrate that even without reducing the time of pump operation (in fact, the time of operation has been increased in 1 h – from 6 to 7 a.m. – in comparison with the previous case) and without moving the pump operation to cheaper periods of the day, reductions in the operational costs can be obtained by adapting the pump operation to the demand flow variation by changing the rotational speed.

3. *Modelling changes in pump operating times:* distinct operating times are considered in this analysis for the pump operation instead of considering the fixed 1-h operating times. The main idea is to reduce the operational cost by reducing the time of operation required by the pump, in this case, of fixed-speed.

The pump patterns are presented in Figure 7(c). The pump is turned-off at 4 h, turned-on between 5 and 5.9 h (54 min of operation), it is also turned-on between 6 and 6.7 h (42 min of operation) and only turned-on 52 min at 20 h in order to avoid the tank to reach the minimum level. During the other periods of the pump operation, the operating time was maintained in 1 h.

Figure 7(c) shows a slightly different pattern in the variation of the tank water level caused by the distinct pattern of the pump operation. However, in this case, reductions were also obtained in the operational costs when comparing to the initial model, due to minor reduction in the pump operating time. Considering the pump constant efficiency of 75%, the values obtained for the network operational cost were 19.82 €. When considering the pump efficiency curve, with a verified average efficiency of 77.8%, the values of the operational cost for the case-study network were 19.10 €. Figure 8(c) is possible to verify the pump operating points resulted from this model considering always the pump nominal speed and distinct operating times, which shows the pump operating at higher efficiency points.

Since the initial solution considered for the periods of pump operation already take advantage of the variation of the energy price, it is not possible to quantify the savings obtained by just moving the pump operation to lower cost periods of the day. However, although not evidenced in the presented results, analysing each time-step individually, the savings in operational costs demonstrated, as expected, to be superior when the reduction of the pump operating time is made for periods of higher energy cost.

4. *Modelling changes in both pump speed and operating time*: a model considering simultaneously non-constants pump relative speeds and different operating times is also analysed. Figure 7(d) shows a set of controls for the case-study considering distinct pump relative speeds and distinct operating times. In this case, the values for the relative speed varies from 0.8 to 1 while the operating time is only reduced in the $7-8$ p.m. time interval, otherwise the limits of the tank levels would not be respected.

Modelling the pump operation with a constant efficiency of 75%, the results for the daily operational cost were 18.78€. On the other side, associating an efficiency curve to the pump, the results demonstrated an average efficiency of 71.8%, meaning that the power consumption is superior in this case, which increases the costs. Observing also the pump operating points with the system and pump characteristic curves provided in Figure 8(d), it is possible to verify that the pump is operating very near the best efficiency points when operating at full speed, n, or at 80% of full speed ($0.8n$). However, when the relative speed is 0.9, the pump is operating at slightly lower efficiency points, which decreases the average efficiency.

Tables 2 and 3 present a resume of the main economical and energetic results obtained with the case-study network considering distinct models based on particular changes in the pump operational conditions and using, respectively, the pump constant efficiency and the efficiency curve.

In a simple network such as the one presented in this case-study, any experienced operator trying to reduce the operational costs will intuitively opt by a kind of network control following the patterns that were already observed in Figure 7. Therefore, a pump would operate essentially during the lower energy cost periods, meaning that the tank will be always emptying during the higher cost period until reach the minimum level.

The first main conclusion that can be taken from the results is that each of the operational analyses deserve attention since, in all cases, significant economical and energetic improvements can be obtained. Reductions up to 13% for the daily costs and up to 9% for the daily energy consumption can be achieved. Such values represent substantial savings.

Another conclusion is that considering a pump efficiency curve, which is a better approximation of a real pump, the percentage of cost and energy reduction is inferior when comparing with the same models using a constant efficiency. Observing the models considering changes in the pump relative speed, when the

Table 2. Results obtained by changing the operational conditions of the case-study network, considering a constant efficiency pump.

Model	Initial	Speed changes	Time changes	Speed and time changes
Avg efficiency (%)			75.00	
Max power (kW)	27.89	27.84	27.92	27.65
Daily cost (€)	21.79	19.12	19.83	18.79
Daily energy (kWh)	276.13	252.92	261.54	248.90
Avg energy (kWh/m^3)	0.44	0.42	0.45	0.42
Pumped water (m^3)	627.7	590.0	590.5	590.5
% Cost reduction	–	12.29	9.00	13.76
% Energy reduction	–	8.41	5.29	9.86
% Avg energy reduction	–	3.64	−1.34	4.96
% Water reduction	–	6.00	5.93	5.93

Table 3. Results obtained by changing the operational conditions of the case-study network, considering a pump efficiency curve.

Model	Initial	Speed changes	Time changes	Speed and time changes
Avg efficiency (%)	77.82	73.25	77.83	71.78
Max power (kW)	26.82	26.79	26.88	26.65
Daily cost (€)	21.01	19.47	19.11	19.54
Daily energy (kWh)	266.14	255.34	252.02	257.07
Avg energy (kWh/m^3)	0.42	0.44	0.43	0.44
Pumped water (m^3)	627.7	590.0	590.5	590.5
% Cost reduction	–	7.34	9.02	6.99
% Energy reduction	–	4.06	5.30	3.41
% Avg energy reduction	–	−2.66	−0.83	−3.30
% Water reduction	–	6.00	5.93	5.93

efficiency curve is used (Table 3), the values of the average efficiency are lower in these cases, implying more power consumption and, consequently, more costs. The lower average efficiencies when reducing the pump relative speeds are also the reason for the inferior percentage of reduction in energy consumption and costs. At the same time, the tests when only the pump operating times are changed, the same percentage of costs and energy reduction are obtained when comparing the cases with constant efficiency and with the efficiency curve. This is because no changes occur in the pump efficiency between the initial case and the case with time changes.

The simultaneous application of pump relative speed and operating times changes does not necessarily provides the lowest value of operational cost. Although, for a constant pump efficiency, the minimum cost were obtained for the model with speed and time changes (Table 2), the same is not observed when considering an efficiency curve. In this case, the average efficiency presented the lowest value (Table 3). However, it should be noticed that the controls options being analysed and assessed may not be the most adequate.

Another important observations are related to the volume of water pumped. Both Tables 2 and 3 show that the changes in the initial operation of the network induced a reduction of around 6% of the total water pumped. It should be noted that a decrease in the operating costs can only be obtained by reducing the volume of water to be pumped or/and by moving the pump operation to more favourable periods of the day according to the energy tariff. On the other hand, a higher volume of water pumped does not necessarily means more energy costs. In Table 3, comparing the model with speed changes with the model with time changes, it is observed that in the model with time changes, a larger volume of water is pumped ($590.5\,\mathrm{m}^3$); however, since the average efficiency is higher, the associated energy consumption and cost is lower. If, on the other side, the efficiency is kept the same (Table 2), an increase in the volume of water pumped will always imply larger operational costs.

As can be seen from Table 3, which provides negative values for the percentage of average energy reduction per cubic meter (meaning an increase), the reduction of the daily energy consumption may not imply lower energy consumption per cubic meter of water pumped. This only occurs in the two cases of Table 2 when the pump speed is reduced, since there is no influence in the pump efficiency.

Both results demonstrate that the approximation of the pump efficiency to a constant efficiency can provide a false perception of the real savings from the use of a variable-speed pump instead of a fixed-speed type. When contrasting with the results obtained by considering a pump efficiency variable with the pumped flow, it is observed that savings in energy and operational costs are smaller but still meaningful.

The pump efficiency is not the only factor that influences the possible savings obtained from the use of VFDs. Several authors have mentioned and discussing other factors such as the geometry (or shape) of the pump impeller and the pump specific speed, which affect the characteristic curve of the pump,[4] or even factors related to the piping system such as the system static head[4,7,8] or the system friction losses,[7] which, in turn, affect the system head curve.

It is known that the existence of a static head in the system curve limits the minimum speed rate allowed for the pump since the pump shut-off head can never be inferior to the system static head. At the same time, the shape of the system head curve, which is also influenced by the friction head losses, can cause the pump curve intersection with the system curve in regions of low efficiency. Friction head losses (considered as a 'major loss') are dependent on the pipes surface material, which increases the viscous effects, and hence the energy loss, with the increase of the surface roughness. The friction losses also include losses due to obstructions in pipes (usually called 'minor losses'). The losses related to the roughness of the pipe surface tend to increase with the age of the pipe. Nevertheless, the influence of changing some parameters in a system head curve is not often quantified in scientific or pedagogic works.

Therefore, the following analyses are also suggested as exercises:

1. *Changing the geometric head:* The initial case-study network, with a static head of 90 m, is used as reference. The same system is tested considering an inferior static head of 30 m and a superior static head of 120 m. For the systems with distinct geometric heads, the 24-h pump controls were adjusted to each network characteristics in order to not violate the system constraints such as the maximum/minimum tank water levels allowed as well as keeping the same tank water level in the begin and in the end of the day and even constraints related to the nodal pressures (which cannot present negative values). The pump controls considered for the systems with a smaller and a higher geometric head are represented in Figure 10. Figure 9(a) and (b) also provides the resulting pump operating points for the two type of controls considered. It is possible to verify that, in the system with the larger geometric head, the speed is never reduced to 80% of the nominal, since the head provided by the pump (see the pump characteristic curve at 0.8*n*) is very close to the minimum head required by the system (120 m).

As can be observed in Figure 10(a) and (c), the use of fixed 1-h time-steps for the pump operation does not allow to reach a final water level equal to the initial. Instead, the final water level in tank is always superior, meaning that more water than the needed is being pumped. Making small adjustments in the pump operating time makes possible to pump only the water needed to satisfy the imposed constraints and, at the same time, allows to reduce the volume of water pumped, implying a reduction in the total energy consumption and cost. The quantified reductions are provided in Table 4.

Observing the results for the savings resulted from varying the pump speed and operating times (Table 4), it is possible to conclude that the pipe networks characterised by smaller geometric heads present greater chances of reducing the operational costs and associated energy consumption. This can be explained by the fact of such systems have more possibilities of taking advantage of the pumps speed variation, which allows an adaptation of the pumps to a large set of flow and head combinations.

In the system with a static head of 30 m (Figure 10(a)), a simple change in the pump operation in the time-step between 20 and 21 h (both speed and operating time reduction) allowed 14.09% of cost reduction with a decrease of 11% in the daily energy consumption. Such improvements are due to a reduction in both the

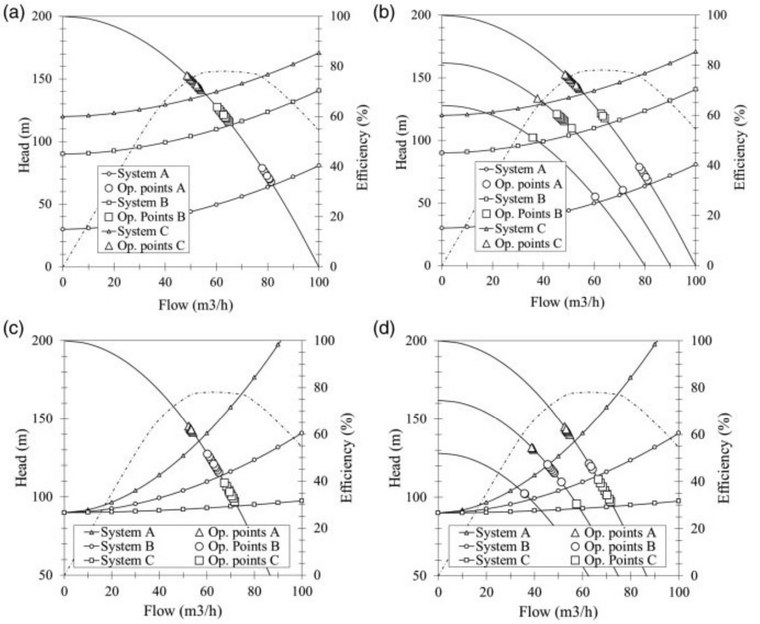


Figure 9. Pump operating points, considering (a) a fixed-speed pump and (b) a variable-speed pump, for three system head loss curves with distinct static heads: (i) system A, with a static head of 30 m; (ii) system B, with a static head of 90 m and (iii) system C, with a static head of 120 m. Pump operating points, considering (c) a fixed-speed pump and (d) a variable-speed pump, for three system head loss curves with distinct pipe roughness: (i) system A, with a roughness coefficient of 30; (ii) system B, the initial system, with a roughness coefficient of 50 and (iii) system C, with a roughness coefficient of 140.

volume of water pumped (reduction of 7.4%) and the average energy consumed per unit of water pumped (reduction of 5.52%).

Concerning the system with the largest static head (120 m), since the pump needs to overcome a greater difference in elevation, more energy is required for pumping the water to the tank. Indeed, this system presents the largest values for the daily energy consumption and cost. At the same time, it demonstrates to be the system with lower chances to improve its operation in terms of cost and energy since, due to the system curve, the pump is not allowed to reduce so much its rotational speed. Since the curve is more close to the initial system (90 m of static head), the savings obtained from reducing both the speed and operating time of the pump are more near to the ones obtained for the initial system. The initial system presented 3.41% and 6.99% of reduction in energy and cost, respectively, while the system with 120 m of static head reduced 4.34% and 5.60% of its daily energy consumption and cost, respectively.

Results presented in Table 4 also shows that, although presenting the larger energy savings, the system with the smaller static head also presents the lower

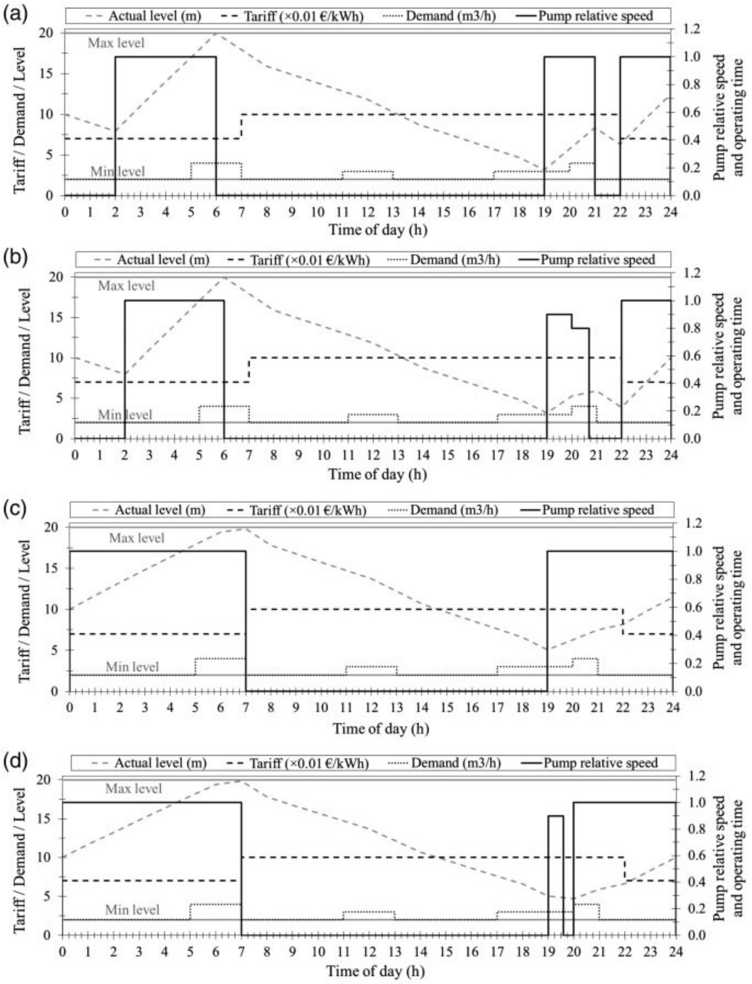


Figure 10. Results for the simulation of 24 h of operation of the case-study network with a geometric head of 120 m considering: (a) a fixed-speed pump with fixed 1-h operating time-steps and (b) a variable-speed pump with variable operating times, and with a geometric head of 30 m considering: (c) a fixed-speed pump with fixed 1-h operating time-steps and (d) a variable-speed pump with variable operating times.

value for the average efficiency when the pump is operating at fixed-speed. As can be observed in Figure 9(a), the system curve does not crosses the pump curve at the best efficiency point, leading to an operation at a reduced efficiency. On the other side, the variation of the pump speed allows to move the pump operation to more efficient points, leading to the highest value of average efficiency (75.06%) when compared to the other systems. This example demonstrates the benefit that the recourse to VFDs can represent in real systems where frequently the pumps are

Table 4. Results obtained from varying the pump speed and operating time in the system of the case-study considering distinct values for the static head: (i) 90 m, corresponding to the initial system, (ii) an inferior value of 30 m and (iii) a higher value of 120 m.

Type of control	Static head (m)	Avg eff. (%)	Daily cost (€)	Avg energy (kWh/m^3)	Pumped water (m^3)	Daily energy (kWh)
Fixed	30	74.07	13.18	0.21	638.13	170.57
Speed	90	77.82	21.01	0.42	627.69	266.14
Time	120	75.35	25.44	0.53	619.58	328.26
Variables	30	75.06	11.33	0.18	590.92	151.81
Speed	90	71.78	19.54	0.44	590.48	257.07
Time	120	74.29	24.02	0.53	590.43	314.03

Savings from pump speed and operating time variation (%)

Static head	Cost	Avg energy	Water	Energy
30	14.09	5.52	7.40	11.00
90	6.99	−3.30	5.93	3.41
120	5.60	−0.81	4.71	4.34

dimensioned considering future requirements of the network, leading to the installation of oversized pumps considering the actual needs.

2. *Changing* the *pipe roughness:* the influence of the pipe roughness coefficients, namely $C = 30$ and $C = 140$ (where $C = 50$ is the value considered initially) is analysed. Lower values of the roughness coefficient are the equivalent to older pipes and usually the higher values correspond to the new ones. The head loss curves that characterise the analysed systems are provided in Figure 9.

Figure 9 shows that lower values of roughness coefficients provide the steepest curves, which are related to the increase of the pipes head losses (already expected according to the classical equations of head losses in pipes). It can be also observed that, although the lower coefficient ($C = 30$) is substantially closest to the initial value ($C = 50$) when compared to the largest coefficient ($C = 140$), such difference is not notorious in the graphical representation of the resulting head losses in the systems. This is explained by a fast decrease of the resistance coefficient with the increase of the Hazen-Williams roughness coefficient. In this case, the pump operation had also to be adjusted to the distinct characteristics of the systems in order to satisfy water levels and pressure constraints. The pump controls initially considered for the systems with lower and higher pipe roughness coefficients are provided in Figure 11(a) and (c), respectively. Table 5 provides the results of energy, costs, efficiency and water pumped for each distinct system.

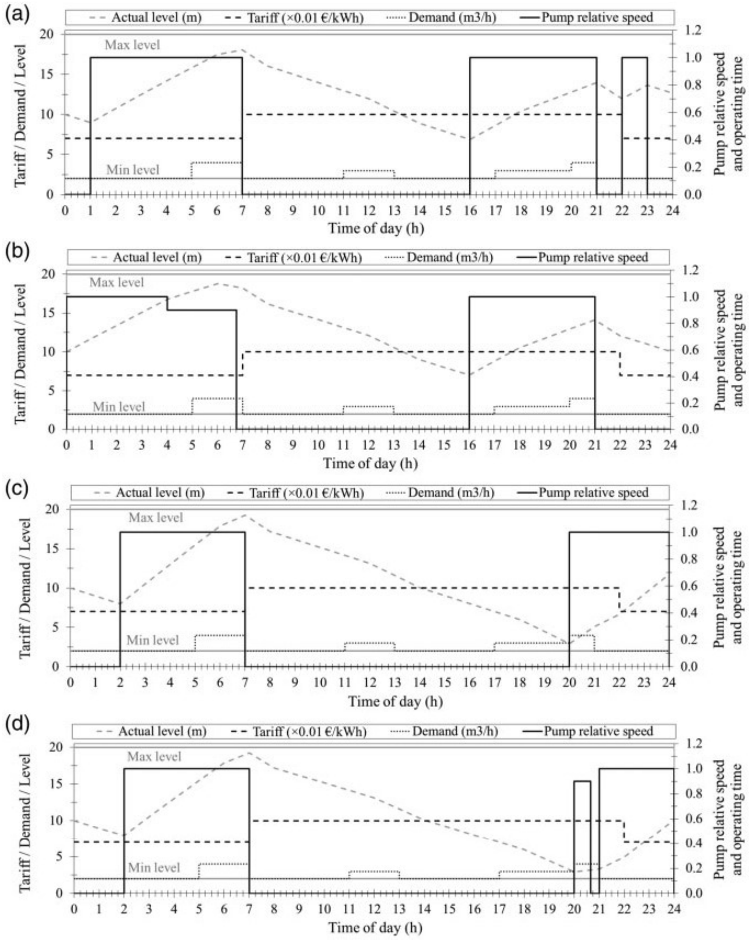


Figure 11. Results for the simulation of 24 h of operation of the case-study network with a pipe roughness coefficient of 140 considering: (a) a fixed-speed pump with fixed 1-h operating time-steps and (b) a variable-speed pump with also variable operating times, and with a pipe roughness coefficient of 30 considering: (c) a fixed-speed pump with fixed 1-h operating time-steps and (d) a variable-speed pump with also variable operating times.

Intuitively, an operator tends to shut the pump off during the high cost period but, in this situation, it is necessary to keep the pump on from 4 p.m. to 9 p.m. Due to the larger pipe head losses in this system, the water level in tank cannot reach lower values than the represented. Otherwise, when the water demand increases between the 20 and 21 h, the pressure in the demand node that is supplied by the tank reaches negative values, i.e. the system is not able to supply the consumers while satisfying the pressure constraints. Even with these limitations in the system operation, some speed and operating time reductions allowed savings in the daily energy consumption and cost of 6.71% and 5.69%, respectively.

Table 5. Resume of the results obtained from varying the pump speed and operating time in the case-study network considering distinct values for the roughness coefficient: (i) the initial value considered 50, (ii) a lower coefficient of 30 and (iii) a higher coefficient of 140.

Type of control	Rough. coeff.	Avg eff. (%)	Daily cost (€)	Avg energy (kWh/m^3)	Pumped water (m^3)	Daily energy (kWh)
Fixed	30	76.04	27.08	0.51	641.64	328.30
Speed	50	77.82	21.01	0.42	627.69	266.14
Time	140	77.38	17.43	0.37	624.37	227.78
Variable	30	73.16	25.54	0.52	590.99	306.28
Speed	50	71.78	19.54	0.44	590.48	257.07
Time	140	77.37	16.19	0.36	591.81	215.25

Savings from pump speed and op. time variation (%)

Rough. coeff.	Cost	Avg energy	Water	Energy
30	5.69	−1.87	7.89	6.71
50	6.99	−3.30	5.93	3.41
140	7.12	0.67	5.22	5.50

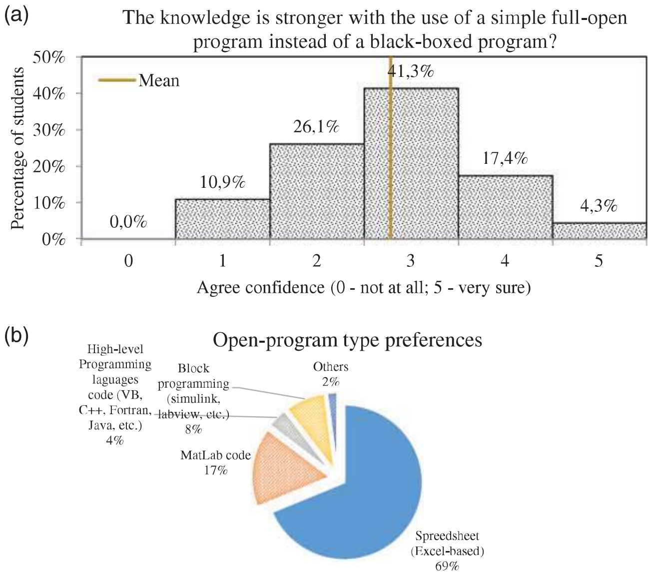


Figure 12. Results of the survey made to students that used the proposed tool: (a) agreement with the fact that the knowledge is stronger with the use of a simple full-open program instead of a black-boxed program and (b) open-program student's preferences.

Results presented in Table 5 demonstrates that the pipe roughness can be a factor that influences the savings obtained from the use of VFDs. Systems characterised by lower roughness coefficients (and hence, higher pipe roughness) resulted in less savings in the operational costs. On the other hand, the system with the lowest roughness coefficient ($C = 30$) presented the highest water and daily energy savings. This can be related to the higher initial values of water pumped and energy consumption due to the operational limitations resultant from the pressure constraints. Also due to this same pressure constraint, the pump operation was maintained during the high cost period which resulted in less cost savings.

Table 5 also shows that the system with $C = 50$ presented the lowest average efficiency when controlled with variable pump speed and variable operating times. This is a result of the pump operating at 80% of its nominal speed, and hence at lower efficiency points, which does not occur in the other two systems (see the operating points at distinct speeds for the three systems in Figure 9(d)).

Conclusion and final remarks

The simple model developed in Microsoft Excel provides a pedagogic, easy and intuitive view of the network behaviour for each hour of the day, providing values of flow, head, water levels variation in tank, head losses, pump power and energy consumption. Both values are in agreement with the EPANET model. However, the Excel tool constitutes a more straightforward, open and clear tool to be used by students than the EPANET programme. Furthermore, several conditions of the network operation are tested, considering distinct speeds and operating times for the pump, and similar results are obtained when compared with EPANET. Such results demonstrate how a well-known and simple tool, such as Excel, can provide an educational and easy way to understand operational changes in a water network and its consequences in terms of energy consumption and costs.

The previous statements were validated by a group of students that used the presented tool in the Fluid Mechanics course. The results of the survey made to the students, represented in Figure 12, show that the knowledge acquired using the proposed tool is deeper than the one obtained using a black-box program. Moreover, concerning the types of open programs, the student's preference is still the use of spreadsheets, as used for the development of the presented numerical tool.

From the advantages presented by the developed tool, some can be highlighted:

- The structure of the tool allows a simple comparison of all the network information during the 24 h of the day with the results obtained by EPANET;
- The tool provides, in a unique table, the hourly information for the characteristics of all the network elements including flows, head losses, consumptions, efficiency, power, energy, costs, levels and volumes, allowing the user to analyse their evolution during the simulated day;
- It is possible to modify any parameter of the pump operation (operating time and relative speed) and automatically obtain the new behaviour of the system

resulting from the operation under the new conditions, both in table and graphical format;
- It allows to change the characteristics of the network elements, such as dimensions, pump efficiency and/or characteristic curve, energy tariff, etc., and visualise the new system and pump curves as well as the resulting behaviour of the model during the simulation period;
- If desired by the user, the method used for the prediction of the pump behaviour operating at distinct speeds can be replaced by others more adequate to a specific pump and/or system;
- The tool reveals to be useful for decision making concerning the installation of a VFD in systems characterised by distinct head loss curves, since it provides the possible benefits from such installation;
- The developed tool also allows to easily implement other additional costs related to the operation of the network that can be specific for each distinct real case;
- The tool is implemented using an Excel worksheet. This kind of software is used by almost all computer users in the world. At the same time, other tools commonly require specific knowledge, which implies additional efforts to the user and may not be practical, for instance, to be used in classes.

As already mentioned by other authors,[6,8] the main improvements obtained from the use of variable-speed pumps instead of the fixed-speed pumps can be achieved in systems characterised by higher variability, taking advantage of the possibility of adapt the pump operating points to the system requirements.

Most of the tests performed in this work demonstrated appreciable savings from the changes applied to the pump operation, namely its operating time and rotational speed. However, it should be noticed that only a specific case-study were tested. When performing this kind of analysis in a real water distribution system, factors related to the system flow/head variability as well as factors related to the pump characteristics, such as dimension and head curve, should be considered.

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Notes

a. Microsoft Excel, a component of Microsoft® Office, is a spreadsheet application developed by Microsoft. Other free spreadsheet alternatives to Microsoft Excel could be used, such as the component Calc of the Apache^{TM} OpenOffice, the Google® Docs spreadsheet, etc.

b. The Microsoft Excel worksheet file is intended for engineering education and can be downloaded from the following website: http://gridsworld.wordpress.com/rd/dimeo/water-grids/. The file can be freely used in courses of hydraulic or fluid mechanics where the students can acquire knowledge for internal flow in pipes, turbomachinery and optimal pump control.

c. The continuity constraint is referred to the tank water level in the end of the simulation that must be equal to the level in the beginning of the simulation in order to provide continuity in the following day (or week, if desired).

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