Towards serious gaming for water distribution networks sizing: A teaching experiment

Daniele B. Laucelli, Luigi Berardi, Antonietta Simone and Orazio Giustolisi

ABSTRACT

Real-life engineering problems relate to different technical aspects to be considered at the same time. Traditional teaching techniques for engineering students (i.e., future decision-makers for such problems) sometimes needs to be supplemented in conveying this complexity, and thus innovative approaches are needed. A new and useful approach allowing a more intuitive understanding of real-life problems is serious gaming (SG), which combines a game environment and utility functions addressed at real problems. This paper describes a first attempt to use SG to help engineering students learn and deal with the complexities of designing water distribution networks given multiple objectives and uncertainty. This application of SG relates to five benchmark water distribution networks, and students were asked to find the optimal value of pipe diameters to minimize the capital cost of pipes. The results of the experiment show that students learn in less time how to design water distribution networks while enjoying the experience. Most students found the approach useful, claiming that the difficulty in approaching the pipe sizing problem decreased considerably as the practice of the game increases. The experiment results can suggest that SG may have value in learning how to design other engineering systems.

Key words | pipe sizing, serious gaming, water distribution network

Daniele B. Laucelli (corresponding author)
Luigi Berardi
Antonietta Simone
Orazio Giustolisi
Technical University of Bari,
Via E. Orabona 4, 70125 Bari,
Italy
E-mail: *danielebiagio.laucelli@poliba.it*

INTRODUCTION

Nowadays, teaching civil engineering faces new challenges, not only regarding the technological and professional skills required for future technicians, but also in terms of evolution of teaching and communication techniques for younger generations. Traditional methods like frontal lessons, use of the blackboard and paper, books, etc., need to be integrated with more applicative approaches, aimed at bringing the learning process closer to students, who are more and more 'digital natives'. Modern educational experts are making increasing use of new pedagogical models, such as experiential learning. They claim that perception, attention, and memory are higher in the presence of active learning (i.e., information that is experienced remains strongly impressed), rather than an educational content delivered through passive methods (e.g., frontal lessons) (Rugarcia *et al.* 2000).

In this scenario, serious gaming (SG) is becoming a valuable tool for a practice-based learning aimed at developing skills or teaching formal contents through a playful interface. The concept of SG involves the combination of several aspects ranging from educational contents to storytelling, from serious purposes to game techniques (see Figure 1). The aim is to provide solutions to real problems representing at once a source of immediate satisfaction. In fact, it was demonstrated that games tend to push players beyond the limits, increasing commitment and determination. The payout is expected to be twofold: (i) surpassing levels with visible results that can be connected to the efforts (win the game); and (ii) contributing in solving real problems (win in the reality). These aspects, together with advances in computer technology, have triggered changes in the world of work and training, thus favoring the rapid increase of SG (Michael & Chen 2005).

doi: 10.2166/hydro.2018.038

Figure 1 | Venn's diagram of serious gaming aims and contents.

In fact, the SG player has the advantage of acting in a controlled environment. Bringing the simulation very close to reality reduces the fear of new experiences and increases the user's expertise in practical applications as well as the confidence in getting involved. The playful environment allows acting spontaneously, without feeling judged by a 'supervisor'. Moreover, the possibility of repeating the exercise several times allows immediate feedback about the system under analysis. This, in turn, increases the understanding of the system and the awareness about possible consequences of the actions in real contexts (Michael & Chen 2005).

The origin of games for training purposes date back to the war simulations ('Kriegsspiel') of the Prussian army of the early 18th century or to the table games of the first half of the 20th century, such as Monopoly. Early military simulations using computers were recorded in the United States in the 1950s at the Johns Hopkins University. Since the 1980s, with the diffusion of video games on a large scale, SG has shown a continuous expansion in various sectors, creating, especially in the Anglo-Saxon countries and in northern Europe, a growing production sector, which has become the subject of scientific research in various disciplines, ranging from engineering to psychology.

Abt (1970) probably used the term 'serious game' for the first time with a meaning close to its current use. He referred to designing serious games used by military officers to study the Cold War conflict on a worldwide scale, as well as non-digital math-related serious games used in schools (Djaouti *et al.* 2011). After that seminal work, the scientific community continuously proposed many SG applications in various fields including healthcare (Brown *et al.* 1997), sport (Harfield 2008), education (de Freitas 2006), politics (Jansiewicz 1973; Sawyer & Rejeski 2002; Kahn & Perez 2009), climate change (Leroy & Saulnier 2013), company management (Schrage 1999), the arts (Graham 1996), etc. More details about concepts and applications on SG can be found in Michael & Chen (2005).

SG can be seen as an educational tool to be used in schools and in many fields of professional activities. In the area of water distribution network (WDN) analysis, planning and management, SG has the potential to facilitate active collaborations between researchers and stakeholders. Exploiting accurate physically based models, even with real data, via simple and playful game interface adapts SG for various WDN problems to everybody (students, researchers, stakeholders, citizens, etc.) (Leroy & Saulnier 2013).

The scientific literature reports several serious games reproducing water systems issues like, for example, water resource management (Rusca *et al.* 2012; Valkering *et al.* 2013; Chew *et al.* 2014; Gaberdan *et al.* 2014; Wang & Davies 2015; Morley *et al.* 2017), flood risk management (Stefanska *et al.* 2011; Rijcken & Christopher 2013; Douven *et al.* 2014), river management and climate adaptation pathways (Valkering *et al.* 2013; Van der Wal *et al.* 2016), water pollution (D'Artista & Hellweger 2007), water supply (Rijcken & Christopher 2013; Bassi *et al.* 2015), or irrigation (Seibert & Vis 2012), just to mention some.

In the governmental sphere, several serious games were developed and applied as technical training to prepare stakeholders for taking decisions in potentially problematic situations dealing with water system management and design. In this way, users can become familiar with limits and rules of different water systems, train on searching the best solutions, increase awareness on uncertainties intrinsic to hydraulic models, and analyze potential alternative scenarios (Kolagani 2016). Finally, SG can be a means to promote collaboration in water management (Medema *et al.* 2016) establishing the basis for active learning in water governance (Evers 2017).

The teaching experiment proposes a serious game developed by the authors, named *Network Pipe Sizing* (*NPS*), to solve pipe-sizing problems related to different benchmark WDNs. Players are students of a master class in hydraulic

engineering. The goal of the paper is to demonstrate the usefulness of the gaming approach in learning network hydraulics. The results of such a first experiment refer to a competition among students who played with the *NPS* game and provided useful information for future wider applications of the same approach. The section below describes the teaching experiment in terms of teaching objectives, serious game environment, and competition rules. Then, the competition results are presented and discussed. Then follows a section in which the opinions of participants are reported and discussed from a teaching perspective. Finally, conclusions are drawn.

THE TEACHING EXPERIMENT

The proposed educational experiment arises from the need to reinforce the knowledge of network hydraulics in the students of the last year of the Master Degree course in Civil Hydraulic Engineering at the Technical University of Bari (Italy). The delivered course of 'Water Systems Management' has the following educational objectives: (1) knowing hydraulic modeling approaches, usually named 'demand-driven' and 'pressure-driven', aimed at supporting the management of WDN; (2) knowing the main approaches for WDN analysis and optimization for supporting different technical tasks (network segmentation, rehabilitation, district design, etc.); and (3) being aware of the capabilities of software tools in supporting the WDN analysis, planning, and management.

Students who attend the course usually have sufficient knowledge of the main concepts of hydraulics and physics, as well as the basic concepts of WDN hydraulics, as a know-how from propedeutic courses such as Hydraulics and Hydraulic Waterworks. Since statistical data on background knowledge are not available (e.g., the average mark in Hydraulics or other previous related courses), teachers use to qualitatively assess it at the beginning of the course through a class discussion, during which the main principles of WDN hydraulics and other related concepts are recalled. Over the years, such a discussion revealed that, beyond a fair background in hydraulics, the knowledge of the real hydraulic functioning of WDNs was quite limited and missed some concepts such as the pressure-driven nature of the water 'demand' components in urban networks (e.g., residential, background leakages, volume-based outflows, etc.) (Giustolisi & Walski 2012). This gap can be attributed to the traditional approaches to WDN analysis and design students learned during basic courses, resorting to the Hardy Cross method and, only recently, to EPANET2 for WDN simulation using trial and error procedures. Moreover, the discussion revealed null or scarce awareness about the multi-objective nature of WDN design problems, assuming that the main objective was to assure pressure at model nodes above the minimum required for a correct service, neglecting some crucial aspects like the minimization of costs or the reduction of pressure surplus to reduce leakages.

Educational objectives

The first part of the course encompassed a classical preparatory phase (i.e., frontal lessons, PowerPoint presentations, short class exercises), in which the concepts of 'demand-driven' and 'pressure-driven' modeling approaches were analyzed in different applications (e.g., design, calibration, planning, etc.). Thereafter, it was decided to introduce SG as an alternative way to deal with WDN design, which would allow students to 'get their hands' on the problem in a controlled, user-friendly and suitable way for their age and expertise. The WDN design problem was the subject of a competition among students, where the goal was to achieve the least-cost WDN sizing solution without pressure deficient nodes.

The educational objectives of such experiment are: (i) understanding the importance of the elements (pipes) of the WDN in terms of diameters (pipe sizing) to find solutions near to the optimum; (ii) bringing students closer to real-life sizing/rehabilitation problems, where different technical aspects must be considered at the same time, including asset characteristics, specific technical purposes, nodal pressure (e.g., avoiding pressure deficient conditions), and budget constraints (cost); (iii) using the game to unveil some key concepts and introduce additional contents beyond those in the traditional course; and (iv) verifying the usefulness of the gaming approach in consolidating the main concepts of WDNs' hydraulics.

Consistently with the aim of promoting the learning process without external constraints, the students took part in the competition on a voluntary basis – about 50% of them

answered positively. Participation in this experiment and success in the competition did not give the right to a higher mark in the final exam.

The used serious gaming tool: *Network Pipe Sizing*

The teaching experiment dealt with WDNs' sizing/rehabilitation using a serious game named *Network Pipe Sizing* (NPS), which was developed for this purpose by the authors. Through the NPS interface, the user gets information on: (1) network structure (layout and asset characteristics); (2) average pressure at network nodes and pressure deficit in the network; and (3) pipeline cost. The player has to change pipe diameters (size) in the network getting information on pressure in each node and related capital cost. The game implements a pressure-driven hydraulic simulation model and can be set to include a background leakage model, based on the software tool WDNetXL (Giustolisi *et al.* 2011).

The game is structured in several levels and the network size (and complexity) increases at each level, requiring that players adapt to different situations and constraints, e.g., size of the network, layout, number of reservoirs, etc. This, in turn, allows testing possible strategies to the final goals. Figures 2 and 3 show the game interface of the first and second level, respectively, reporting their optimal solutions.

The next three networks come from the technical-scientific literature: Gessler (Gessler 1985), Hanoi (Fujiwara & Khang 1990), and Apulian (Giustolisi *et al.* 2008). From the sixth level onwards, NPS implements real WDNs serving municipalities in the Puglia region (Italy) (over 200 WDNs), sorted by increasing topological complexity (i.e., increasing the number of nodes).

The game has a very simple graphical interface: squares represent reservoirs (i.e., fixed hydraulic head) and circles represent nodes, where the color ramp on the left, from botton to top, indicates the nodal pressure condition (from pressure deficient condition up to that required to satisfy water requests). Information on nodal demands and elevations are not available in the current version. This choice is aimed at simplifying the game avoiding giving too much information to the player, thus moving him/her away from a more traditional design exercise towards a 'pure game' condition. However, this lack of information could push students in formulating hypotheses on possible causes of simulated WDN

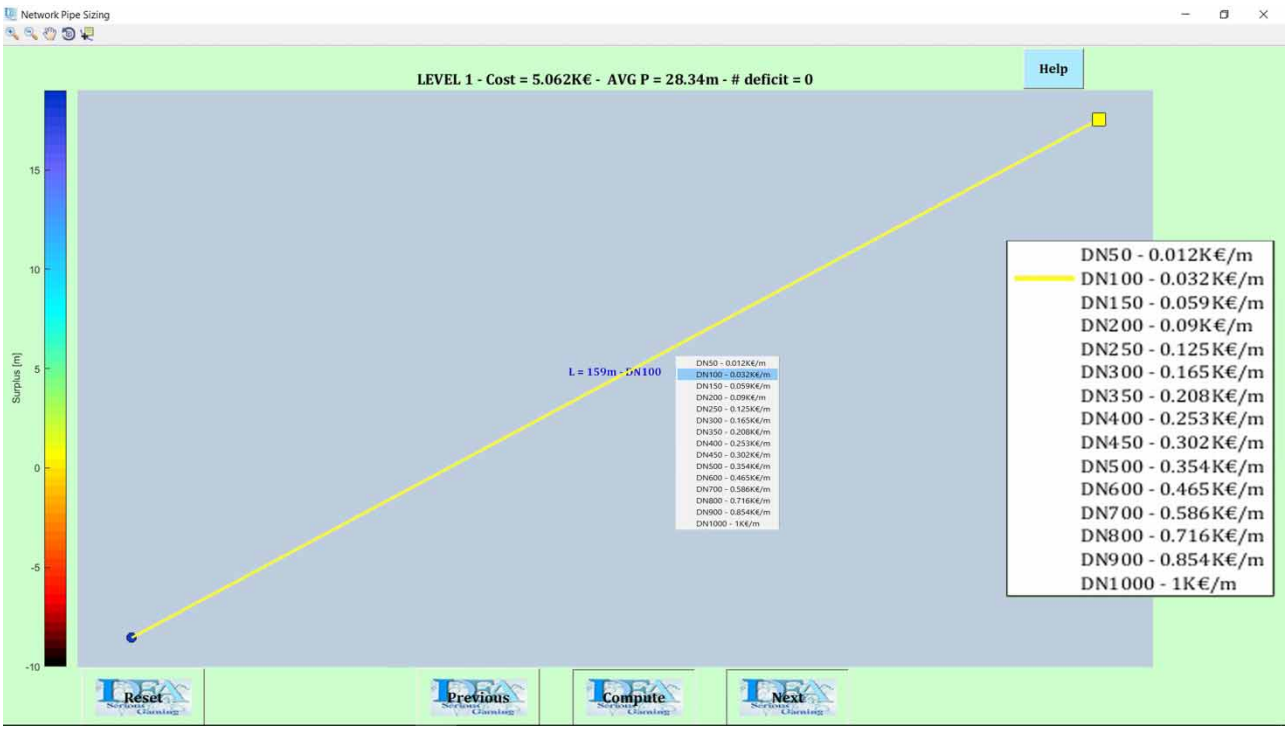

Figure 2 | First level of the NPS game for WDNs' sizing/rehabilitation.

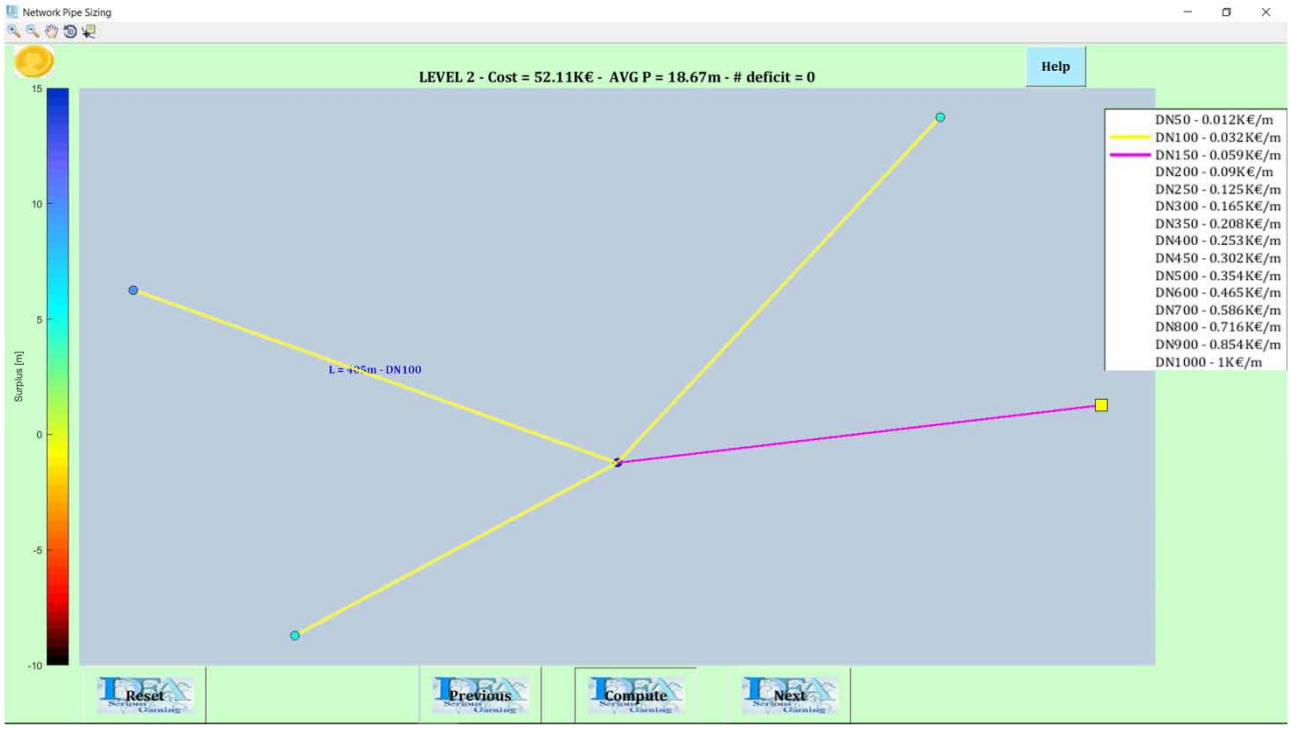

Figure 3 | Second level of the NPS game for WDNs' sizing/rehabilitation.

hydraulic behavior under alternative sizing configurations as well as emphasizing the concept of uncertain demands in real systems. Nonetheless, knowing this information might induce players to reproduce the network on other software packages, maybe using automatic optimization procedures, which were not allowed in the competition.

Regarding pipes, the used version of the NPS tool shows length and diameters as key information to drive pipe sizing. The user can only modify pipe size among 15 diameter classes, from DN50 to DN1000.

To select a diameter for each pipe, the user must press the right button of the mouse and simply choose from the menu that appears (see Figure 2). Once selected, a label for the nominal diameter (e.g., DN150) and a color code (see window on the right in Figure 2) indicates the pipe characteristics, including cost per unit length. The color coding was introduced to facilitate WDN understanding, especially for more complex networks (see Figure 4, for example).

The graphical user interface contains also:

The COMPUTE button. Once clicked, this button runs a hydraulic pressure-driven simulation, including background leakages along pipes. Consistently with the main rules of the game, except for pipe diameters, the user cannot modify the boundary conditions of the hydraulic simulation like nodal demand and elevation, topology, head in reservoirs and, if it is the case, deterioration parameters of the leakage model. The simulation returns the pressure values (in color scale) in each node and the total pipe cost of the solution. These results help the user to evaluate how the changes in pipe diameters change total cost (cost [K€]) and average pressure (AVG P [m] (see Figure 2). After the hydraulic simulation of each tentative solution, nodes with pressure deficit (i.e., pressure lower than that for a satisfactory supply service) are the two top right circles and their total number is shown in the upper part of the interface (#deficit). This way, the user can focus on more problematic nodes/pipes of the network, trying to eliminate pressure deficient nodes.

The RESET button allows restarting from level 1 losing all the levels passed until then.

The NEXT button allows the user to access the next level if he/she considers the current solution as optimal.

The PREVIOUS button allows going back to the previous level to refine the solution.

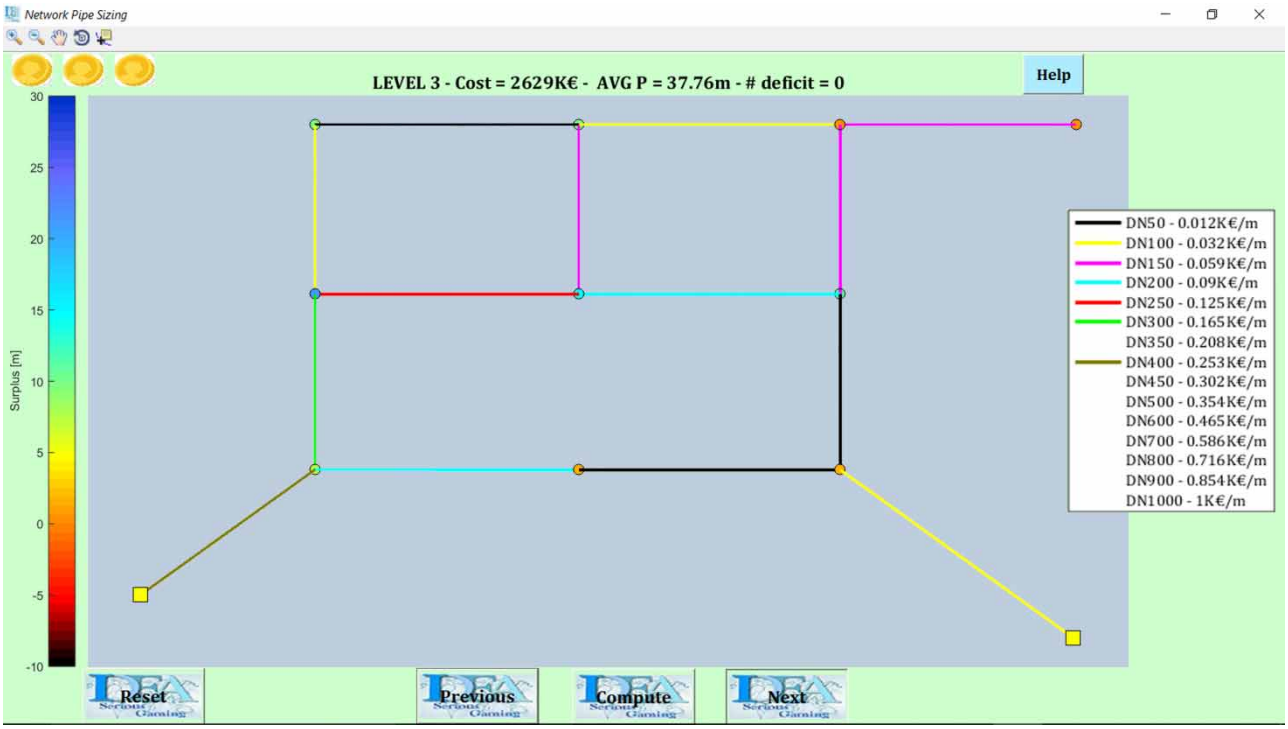

Figure 4 | Optimal solution screenshot of the third level of the NPS game for WDNs sizing.

The HELP button provides, in brief, information about the game modes.

When a solution without pressure deficient nodes is achieved, the user can go to the next level; in this case, a 'coin' is gained, no matter what the total pipe cost and AVG P. Only in the case that the user already has a coin, can he/she can pass to the next level, even with some deficit nodes, thus losing one coin. In other words, the user must reach at least the #deficit = 0 to pass to the next level without spending coins.

It has to be noted that, in the used version of the NPS tool, there are no constraints/data on running time on each network. This aspect definitively leaves time for the user/student to make some physically based reasoning on each solution, getting continuous feedback from trying alterative configurations.

Competition rules

The teaching experiment presented herein involved 41 students of the last year of the Master Degree course in Civil Hydraulic Engineering, for two consecutive academic years (26 students in 2017 and 15 in 2018). The experiment was conceived as a competition among students, where the goal was to achieve the least-cost WDN sizing solution without pressure deficient nodes.

Each student worked individually at home, in the maximum time of 1 week, without comparing results with other colleagues. In order to limit the complexity of the competition, the students were asked to provide solutions for the first five levels/networks only. The solutions of the first two (simplest) levels (see Figures 2 and 3) were not considered for the evaluation of results, but rather they were an initial 'worm up' (i.e., a sort of training) to the game and its features. This way, the users (students, researchers, etc.) could become familiar with the game.

The sum of the network cost of the three last levels was the overall figure to be minimized for each student. In has to be noted that the optimal target cost of each network/level was not provided to the participants before the competition in the first year (2017), while it was in the second (2018). This means that the first batch of students operated without having any clear target, as generally happens in real-life problems.

In level 5 (Apulian network), the NPS was set by the teachers (authors) to include a leakage model as proposed by Giustolisi *et al.* (2008), although the students did not know about the presence of such leakage model before playing the game. The reason for omitting such information was to test if students were able to grasp the differences between the expected behavior, based on the first four levels without leakages, and the simulation results of the last network.

Furthermore, the students were explicitly told that for the evaluation of results, the average pressure in the network (AVG P) would not be considered. In fact, in real pipe sizing problems, the minimization of average network pressure is usually not requested, and the absence of deficit nodes is assumed as a sufficient indicator for hydraulic suitability of the solution. Nonetheless, based on the information on AVG P, students may note that alternative solutions, with similar costs, can result in different average pressure, linking this with the expected effects on leakages as explained during the course.

Additionally, since the game consists of changing the diameters of pipes and getting feedback on pressure, the students are driven to consolidate the understanding of head loss formulations (i.e., proportional to pipe length and to power −5 of pipe diameter) which is behind the hydraulic simulation of the WDN.

Evaluation methodology

The final evaluation of the results followed three steps. The first step consisted of the elaboration of basic statistics of the results provided by the students.

The second step consisted of a classroom discussion about the results and new know-how and awareness acquired by the participants. During such a discussion no individual questionnaires were used, but the interviews were carried out at classroom level following a list of relevant points prepared by the teachers that was extended to additional issues that emerged during the discussion. The discussion was open also to students who did not participate in the competition, aiming to facilitate the transfer of concepts among students, without penalizing those who decided not to participate in the competition.

In the last step, the teachers elaborated on the information and drew conclusions related to the learning objectives. It has to be noted that the third step is really completed only after the student passes the final exam, when the teacher can really test the abilities of the student, also in comparison with those that did not take part in the game.

THE EXPERIMENT RESULTS

In the following, results for the third, fourth, and fifth levels are reported and discussed. Please note that they both refer to an optimal solution used as reference point for the considerations reported. Despite the final goal known to students being the sum of the network cost of the three levels, the results are discussed considering the levels separately, in order to highlight the difficulties and common behaviors in each level of difficulty.

Level 3: Gessler WDN

Figure 4 shows the optimal solution for the Gessler network used for this experiment. The network consists of 2 reservoirs, 14 pipes, and 10 nodes. This network is quite simple, although the two reservoirs can introduce a significant difficulty from the design point of view, especially for inexperienced users (students).

Figures 5 and 6 show some diagrams summarizing the results of the sizing experiment/game as performed by the students, respectively, in the first year of experiment (2017) and in the second year (2018). Diagrams on the left of Figures 5 and 6 show the cost of the WDNs designed by the students for the 2017 and 2018, respectively, normalized to the cost of the optimal solution, reported in gray on the left of the x-axis.

Therefore, the optimal solution is identified by the value 1, while the solutions of the students are all larger than 1. The gray shadowed band in the diagrams on the left of Figures 5 and 6 show a maximum difference of 10% from the cost of the optimal solution, and, the solutions included in this band are considered as very good.

The diagrams on the right of Figures 5 and 6, instead, show the frequency of solutions that fall into pre-established classes of cost difference from the optimal solution, built with a constant step of 5%.

In 2017, there were only three students who came very close (below 10%) to the target, while most of them were

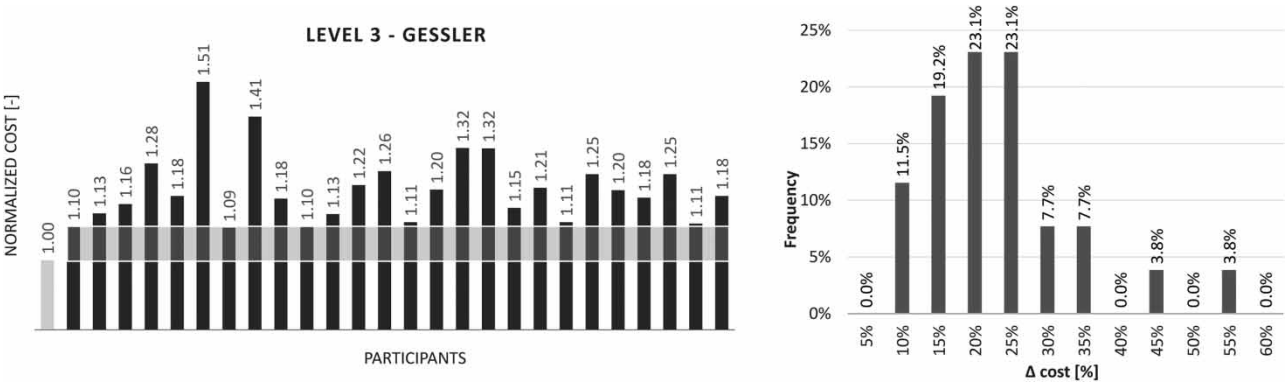

Figure 5 | Third level: Costs normalized with respect to the optimal solution (left); frequency of cost classes as increase with respect to optimal solutions (right) – 2017.

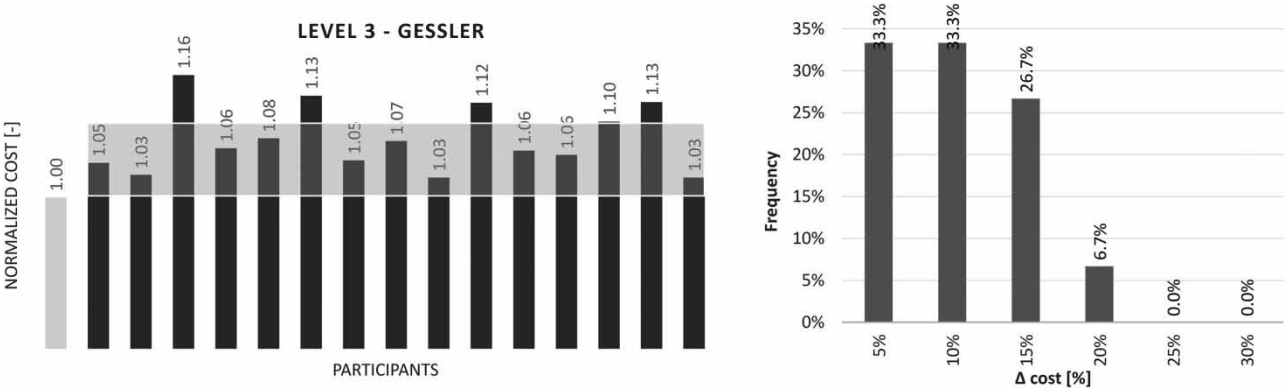

Figure 6 | Third level: Costs normalized with respect to the optimal solution (left); frequency of cost classes as increase with respect to optimal solutions (right) – 2018.

between 15% and 25%. In 2018, 33% of them stayed below 5% of the optimal solution and 66% were within 10%, so very close to the optimal solution. Maybe, the knowledge of the target cost motivated students to place themselves beyond the initial results. Finally, about nodal pressures, in 2017 the value of the average network pressures (AVG P) obtained by the students was on average equal to 38.6 m, with a standard deviation of 3 m, while in 2018 the values were 38 m and 1.9 m, respectively. This means that near-to-optimal solutions are quite similar to each other and result in reduced excess of pressure, with a possible positive effect on asset deterioration and leakages.

Level 4: Hanoi WDN

Figure 7 reports the optimal solution for Hanoi network used for this experiment. The network includes 1 reservoir, 34 pipes, and 31 nodes, with a heterogeneous range of diameters (i.e., 13 out of 15 available) in the optimal solution.

The specific characteristic of this network is the presence of many serial nodes, i.e., nodes that have only one inlet pipe and only one outlet pipe. This circumstance makes it difficult for students to reach near-to optimal solutions, also because they did not know the nodal demands and elevations.

In 2017, only one student managed to stay within 10% difference from the cost of the optimal solution, while the majority was between 20% and 30%. In addition, three students were probably satisfied with the result obtained during their first attempts and accepted a solution that cost 50% more than the optimal one without putting in further effort (Figure 8).

This general difficulty was confirmed in 2018, although the target cost was known in advance.

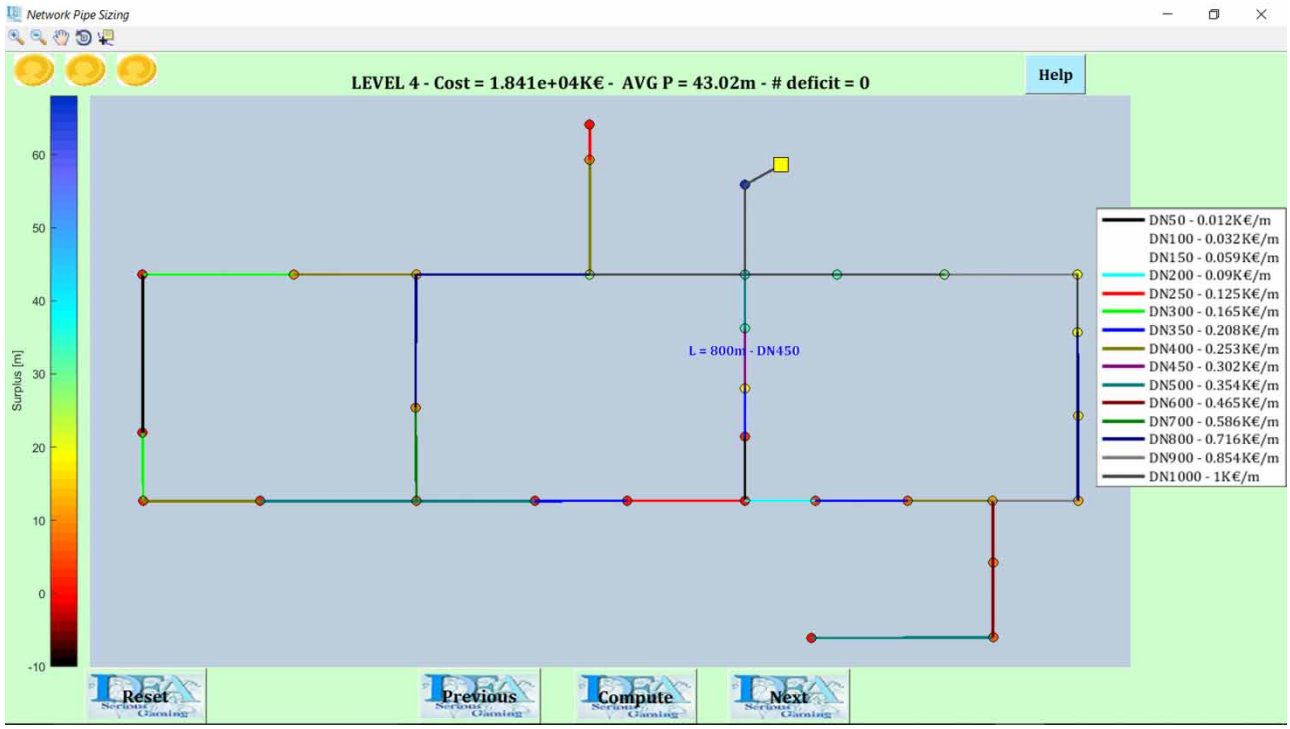

Figure 7 | Optimal solution screenshot of the fourth level of the NPS game for WDNs sizing.

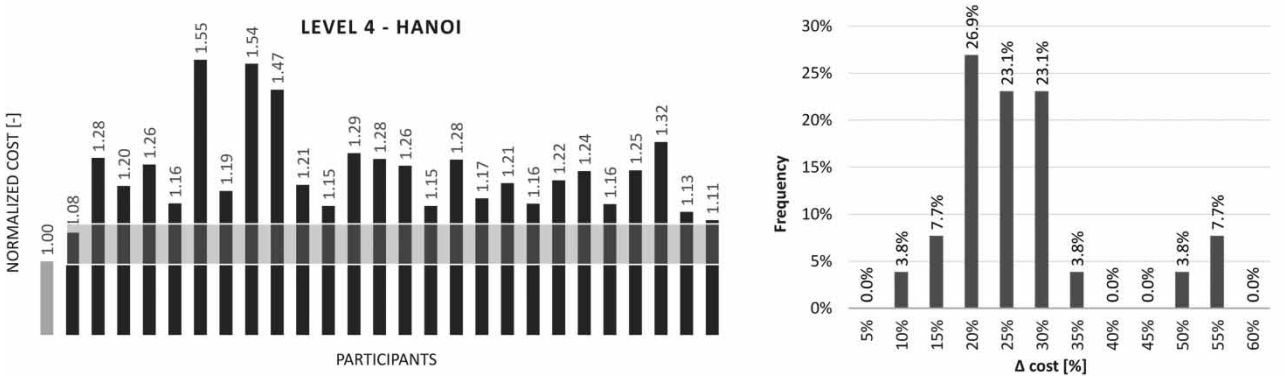

Figure 8 | Fourth level: Costs normalized with respect to the optimal solution (left); frequency of cost classes as increase with respect to optimal solutions (right) – 2017.

In fact, only one student (student number 2, who had already performed well at level 3) was able to stay within 10% of difference from the optimum (even reaching the target), while the majority was between 20% and 35% of cost increase (Figure 9). This result clearly showed the difficulties in designing a network apparently simple like Hanoi, even knowing the cost of the optimal solution.

Finally, regarding simulated pressures at nodes, in 2017 the average network pressures (AVG P) obtained by the students was 43.8 m, with a standard deviation of 4.4 m, while in 2018 the values were, respectively, 47.6 m and 1.5 m. This figure, beyond the three outliers mentioned above, confirms that in 2017 the tendency was to prefer the lowering of the average pressure even if increasing the network cost. In 2018, once again, the knowledge of the target optimum

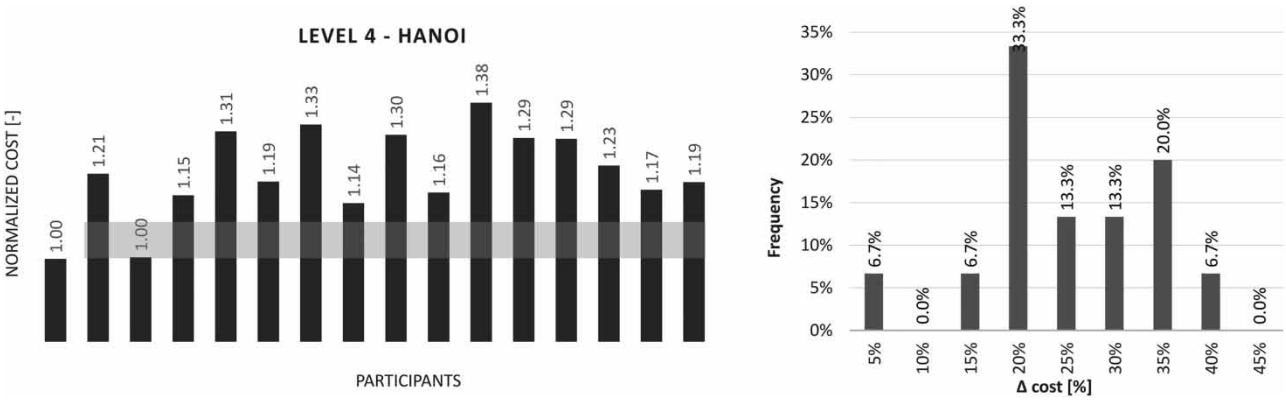

Figure 9 | Fourth level: Costs normalized with respect to the optimal solution (left); frequency of cost classes as increase with respect to optimal solutions (right) – 2018.

has moved the attention of students from the minimization of AVG P towards cheaper solutions, but bringing them to similar configurations, as demonstrated by the low standard deviation.

Level 5: Apulian WDN

Figure 10 reports the optimal solution for Apulian network, which is the last level considered in the experiment. This network has 1 reservoir, 34 pipes, and 23 nodes and, differently from the previous levels, includes a pressure-dependent leakage model as defined in Giustolisi *et al.* (2008). This network is more looped than the previous ones and introduces some difficulties in sizing because of the leakage model, i.e., a component of water 'demands' that does not refer to the service pressure only (observable indirectly by the students through the number of pressure deficit at nodes). This, in turn, allows introducing novel

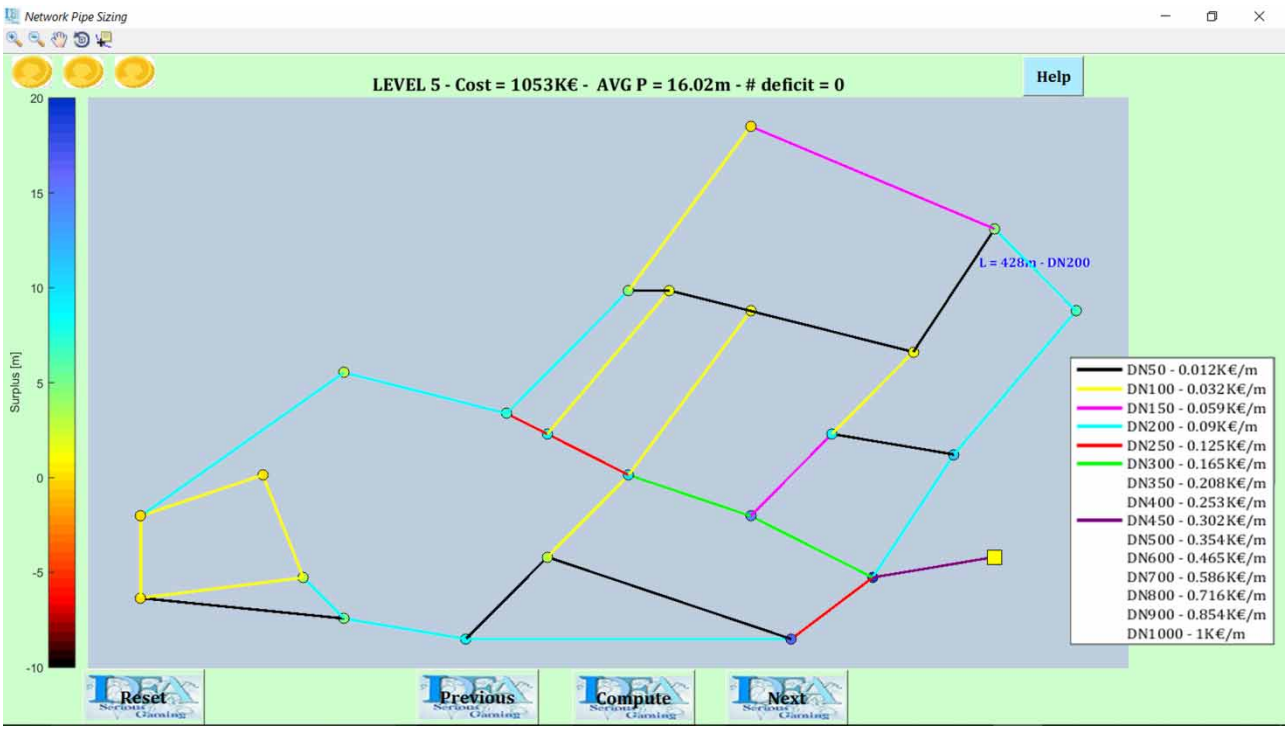

Figure 10 | Optimal solution screenshot of the fifth level of the NPS game for WDNs sizing.

elements with respect to the knowledge acquired through previous levels.

For 2017, one of the students obtained a solution very close to the optimal one, while the majority was between 20% and 50%, confirming the difficulty of solving the sizing problem in this network. In particular, there were some students that formed the solution on the first attempt, clearly oversizing the network (see Figure 11 (left)).

In 2018, except for two students who performed within 15% increase from the optimal cost, the majority managed to stay within a maximum difference of 40%, with a couple of students who were satisfied and closed the game at the earliest attempts (see Figure 12).

Finally, regarding nodal pressures, in 2017 the average value of AVG P obtained by the students was 16.7 m, with a standard deviation of 1.8 m, while in 2018 the values were, respectively, 16.2 m and 0.9 m. For this level, the 2018 students have once again obtained very similar solutions regarding the configuration of diameters, compared to their colleagues in 2017, although with a slight difference in the average values.

CLASSROOM DISCUSSION OF THE EXPERIMENTAL RESULTS

The above-mentioned results of the competition from all the participants were discussed at classroom level. This way, participants had the opportunity to report negative aspects of the used serious game (NPS), discuss practical and theoretical concerns with the SG approach, report knowledge and awareness gained with respect to the background theory delivered in traditional lectures. The discussion was driven by the teachers (i.e., the authors) and students could respond freely, leaving room for additional issues. Each level of the game was analyzed, going into more

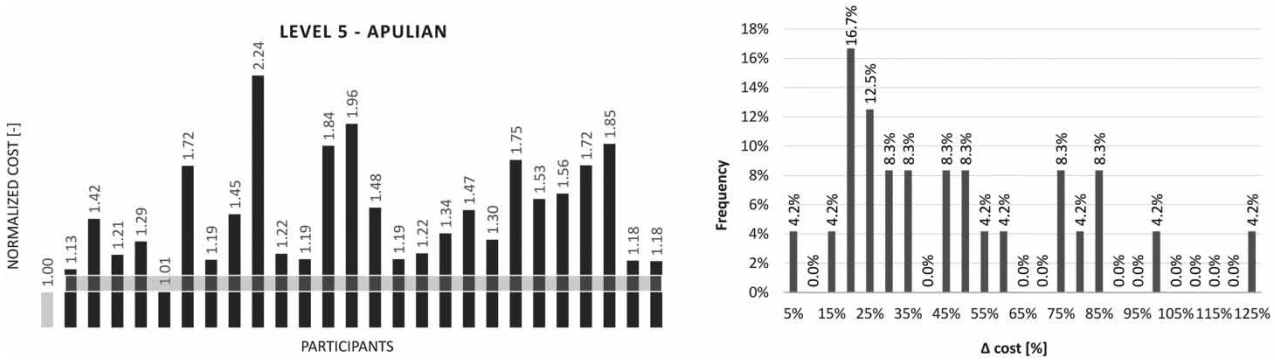

Figure 11 | Fifth level: Costs normalized with respect to the optimal solution (left); frequency of cost classes as increase with respect to optimal solutions (right) – 2017.

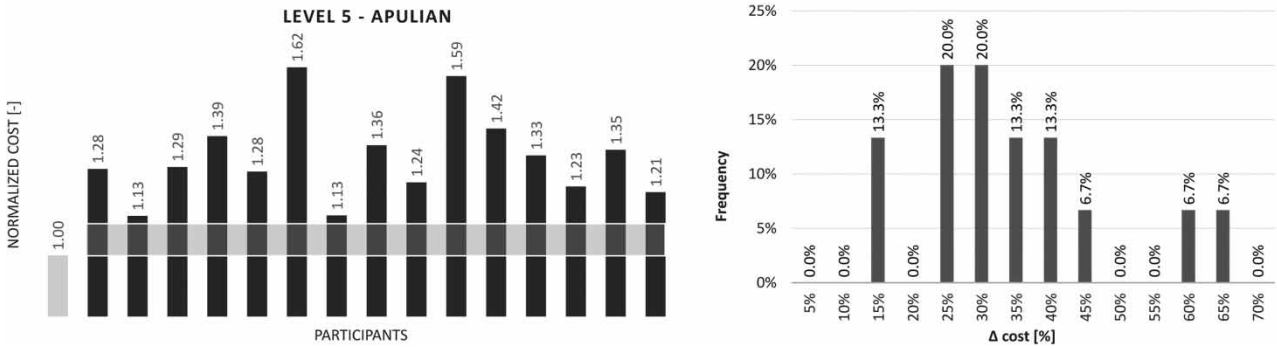

Figure 12 | Fifth level: Costs normalized with respect to the optimal solution (left); frequency of cost classes as increase with respect to optimal solutions (right) – 2018.

detail on the hydraulic aspects of each network. The students reported their experience on SG and suggestions.

In this section, the contents of the discussions with students in 2017 and 2018 are reported in brief. The students agreed that the game has a very simple graphical interface and is very intuitive and suitable for easy transfer of concepts. Everyone agreed that the first two levels were useful in training on the functionalities of the tool.

Most of the students reported that they used a strategy to get the solutions as a basis for overcoming the game levels. They noticed that a balanced network in terms of pressures is synonymous with a well-designed WDN. It was reported that the strategies used to pass in the first levels were changed in order to account for the differences among various game levels. For example, they decided to insert large diameters close to the reservoirs and gradually reduced them going towards the end of the network but, for looped networks (e.g., Apulian), they felt the need to close links in order to better control higher pressures. Many of them realized they would need valves to close some pipes but, since this was not possible in NPS, they inserted small diameters to simulate the closure of the links as higher head losses.

One of the ideas that was consolidated among the students regarded the uniformity of diameters, i.e., not having abrupt passages from large to small diameters but proceeding gradually from the larger to the smaller commercial diameter. This led to the circumstance that many of them did not reach (or get closer to the optimal solution) simply because of this constraint on avoiding abrupt transition between diameters (e.g., from 50 mm to 200 mm, for example). Probably, this assumption was the motivation to link network compactness to homogeneity in diameters, resulting in a few diameters for compact networks (e.g., Apulian or Gessler).

On the contrary, the presence of stretched networks (i.e., networks developed predominantly along one direction) led to the opposite perception, that is, stretched networks are synonymous with heterogeneity of diameters. This idea, associated with the fact that the presence of many reservoirs is often neglected, resulted in sizing stretched networks through a series of pipes with decreasing diameter, as in the case of level 4 (i.e., Hanoi network). Another factor determining a wrong choice of diameters was the length. In fact, a few students admitted they neglected the relationship that may exist between length, diameter, and pressure for network sizing.

Regarding the consideration of the average pressure in the network (AVG P), the students were explicitly told that for the evaluation of results it would not be considered. Consequently, each student decided independently to achieve a specific pressure minimization for each level, considering that NPS does not ask for a certain value of the average pressure to pass the level, but rather asks for not having pressure deficits (for which it gives a coin). From the interviews with the students in 2017, it emerged that, without having a clear target, they took average pressure as a high consideration, sometimes accepting higher costs. This could be related to a more pronounced attention of students to adequately supply water to customers, rather than matching the mere economic aspect of the problem. In 2018, the knowledge of the target cost definitively shifted students' attention to the economic side of the game/problem (i.e., approaching that value to win). This aspect, however, caused that all students converged towards a similar configuration of diameters, from which derives a lower standard deviation of the values of the average pressures and a lower average value of the AVG P of the solutions.

Regarding the rule of earning coins if the solution has no pressure deficits, students of both years reported that the reward mechanism is certainly an incentive to find solutions that are not that 'cheap'. In addition, the lack of a limit in the opposite direction (i.e., obtaining very expensive solutions with very high pressures) can lead to passing the level without too much effort.

During the interview it was neither possible to detect how many students used coins to move to the next level nor the levels when coins were actually used by the students, simply because such events were not recorded in the current version of NPS. By students' admission, they did not use coins to pass the levels in the competition. This fact suggested including the record of such information in future implementations of the NPS tool as well as possible modifications to the reward mechanism. For example, the coin value could be directly proportional to the complexity of the network designed without deficit or inversely proportional to the difference from the optimal minimum cost.

Students realized that zoned sizing is not always a feasible solution, because every part of the network is linked to others and the network needs to be considered as a whole.

Another interesting point of the discussion is the effect of the leakage model in level 5. Students in both years admitted that the simulation of background leakages can be useful for correctly reproducing the WDN hydraulic functioning. In both years, however, the presence of the leakage model in the Apulian network perturbs in some way the concepts experienced in the first four levels. For instance, the consequentiality between decrease in diameter (and therefore the cost) and decrease of the average pressure (or the deficit onset) is not always verified in the Apulian case, because the effect of reducing diameters on pressure have a different impact on water demands due to leakages.

The discussion also showed that knowing the target cost led the students in the right direction, forcing them to make several attempts to approach the objective, and resulting in similar solutions among participants in 2018. This information was considered and included in the competition among students in 2018, because students in 2017 claimed that they were not confident in proceeding 'blindly' towards the target.

Finally, the discussion moved towards a wider perspective of the WDN design approaches. Both groups (i.e., 2017 and 2018) concluded that, even with a good knowledge of network hydraulics, optimization processes can be very useful, both in terms of time and goodness of results, even for small networks. Vice versa, classic trial and error approaches can hardly lead to close-to-optimal solutions for WDN with real complexity.

EDUCATIONAL RESULTS

The teaching experiment took place on 41 independent statistical samples (students in this case) aiming at three educational results as mentioned above. The independence of the participants was assumed as an important condition to carry out the experiment, in particular to reproduce the learning process that usually takes place during classroom lessons and the following individual study at home. In fact, the learning objectives were focused on the individual student and not on team work.

For the participants, this situation requires the use of all their knowledge and skills to solve the problems at various game levels. They had the opportunity to train gradually while developing skills, and test by themselves individual strategies to solve the problems.

NPS gave students the opportunity to immediately put into practice some of the information learned during the course, thus minimizing the forgetfulness curve, using gamification elements to increase their motivation. Actually, most students claimed that the game gave them the opportunity to test their previous knowledge on quasi-real cases. The students moved from the role of passive observers to that of active decision-makers, increasing their awareness of each decision they took.

A common point in both years is that the students confirmed that the approach to WDN design by means of NPS was much simpler and more intuitive than in other similar courses, with traditional methods and supports (books, tables, calculators, worksheets, etc.).

Regarding the objective (i), discussion revealed that the experiment helped them to discriminate those aspects of network hydraulic behavior that are useful for WDN sizing problems, and to realize that much depends on the particular network analyzed. Additionally, they have managed to better perceive some relationships they previously only knew in terms of formulas (e.g., relationship that may exist between length, diameter, and pressure for network sizing).

Regarding the objectives (ii) and (iii), the discussion emphasized the need of closing pipes, in order to control higher pressures in looped networks, because the game does not allow placing of closed valves. During the remaining part of the course such conclusions were actually useful to introduce and consolidate concepts like, for example, the need of network segmentation/district design to enable pressure management. Such problem was faced from both an operative (open/close valves) and a modeling (i.e., the difference between having a small diameter link or a valve) point of view (Laucelli *et al.* 2017).

Finally, the final exam marks of the participants were considered as a possible indicator about the usefulness of the gaming approach in consolidating or learning the main concepts of WDNs' hydraulics (objective (iv)). To this purpose, Figures 13 and 14 report the final exam marks of the students (both participants in the experiment and not) and show that those who participated in the experiment passed the final exam with higher marks on average. This result hints that

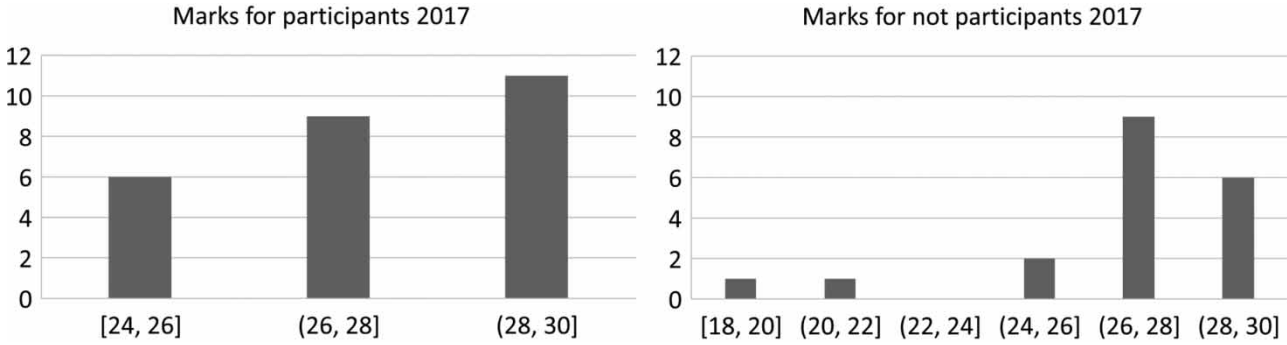

Figure 13 | Final exam marks (grouped) of the participants in the experiment (left) and non-participants (right) – 2017.

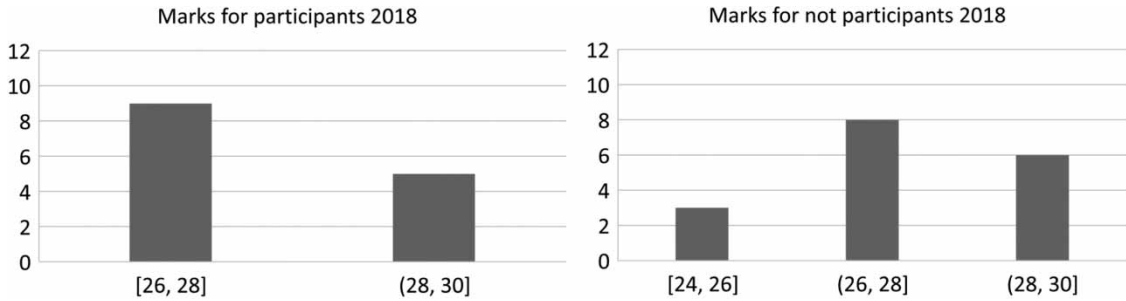

Figure 14 | Final exam marks (grouped) of the participants in the experiment (left) and non-participants (right) – 2018.

the teaching experiment did contribute somehow in their improving learning. In these figures, the marks on the x-axis are grouped in pairs. Please consider that in Italy the maximum mark is 30 and the minimum to pass the exam 18.

From the analysis of Figures 13 and 14 it is possible to note that participants in 2017 were able to pass the exam with higher marks than other students; in particular, those with the highest marks doubled among the participants. This trend is not fully confirmed in 2018, when among the participants there are still very good marks, but the percentage of high marks (28–30) is identical between the participants and the non-participants. This brief analysis is certainly neither exhaustive nor definitive and further tests should be targeted to better quantify the effects of SG in the learning process.

CONCLUSIONS

The presented teaching experiment reports the results from the use of SG as teaching and learning methods in hydraulic engineering. It shows that game-based learning can represent a potentially useful tool for fixing the main concepts of network hydraulics, introducing new concepts (for example, related to WDN management) and beneficially supplementing more traditional teaching approaches available to transfer knowledge and gain experience in WDN functioning.

The interactive nature of the SG simplifies the understanding of the problems and allows concrete management and analysis issues to be dealt with. In fact, by playing the game: (i) the case studies become familiar, (ii) much more awareness about the topology and the hydraulic behavior are immediately learned, and (iii) the opportunity is given to repeat the exercise and avoid stressing contexts while analyzing quasi-real situations through the game.

This means that users can try to solve problems using several strategies by instantly verifying their validity. Most students found this approach useful, confirming that the trial and error strategy helped in consolidating concepts related to the functioning of WDNs as well as the possibility of analyzing different network typologies. The discussion

following the experiment allowed building a shared knowledge base about WDN functioning. This, in turn, made easier the introduction of concepts different from those dealt with in the experiment (e.g., optimization, pressure management, network segmentation/district design) but related to them, facilitating both the teacher's activity and the student's learning.

Finally, it should be emphasized that the serious game used for the experiment (NPS) is in its first version and in the future its game-like elements will be developed further to unveil their contribution to learning more clearly. Possible evolution of the approach in the same WDN management areas could prove very promising also for applications in professional environments (researchers, technicians, water utilities, etc.).

ACKNOWLEDGEMENTS

The authors wish to thank all the students from the master class in Hydraulic Engineering at the Technical University of Bari who participated in the competition that made this work possible: Bavaro Leonardo, Berardi Francesco, Calabritta Sara, Cannito Pietro, Capobianco Gianvito, Cappelluti Francesco Paolo, Carone Maria, Cassatella Antonia, Cipriano Lorenzo, De Pompa Alberto, Di Gregorio Antonio, Dibisceglia Matteo, Dipaola Francesco Claudio, Favia Elisabetta, Fiore Giuseppe, Freda Manuela, Iacovone Gianluca, Lappola Federico, Laquale Ivano, Mancini Alessandra, Maraglino Domenico, Marchese Chiara, Martino Carlo, Miniello Alma Francesca, Miroballo Ciro, Motolese Gaetano, Nanocchio Pasquale, Nembrotte Menna Fabio, Nesca Francesco, Nunziato Martina, Pannarale Grazia, Peluso Erika, Petito Francesco, Pietrangelo Tullio, Pulito Susanna, Riglietti Alessandra, Rinaldi Giuseppe, Salvatore Gabriella, Siena Delia Anna, Vivilecchia Roberto, Winiarska Ewelina.

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First received 24 April 2018; accepted in revised form 12 November 2018. Available online 11 December 2018