UNIVERSITY OF CASSINO AND SOUTHERN LAZIO

DIPARTIMENTO DI INGEGNERIA CIVILE E MECCANICA

MASTER SCIENCE THESIS IN

CIVIL ENGINEERING

URBAN WDN OPTIMIZATION CONSIDERING UNCERTAINTY OF FIRE EVENTS

THESIS SUPERVISORS	STUDENT
Prof. Rudy Gargano	Alessandro Farina
Prof. Leonardo Alfonso	0041576
THESIS CO-SUPERVISOR	
Prof. Carla Tricarico	

ACADEMIC YEAR 2019/2020

All humans die

but

few have lived,

and you will forever

live in our hearts and minds,

Antonio.

ABSTRACT

URBAN WDNs OPTIMIZATION CONSIDERING UNCERTAINTY OF FIRE EVENTS

Multi-Objective Optimization methods and techniques are nowadays largely used and well known to be effective to approach both design and operational aspects of water distribution networks for urban potable water supply. When a WDN is also designed for firefighting purposes it is important that hydrants on the streets are capable to meet certain requirements in terms of adequate flow and pressure in order to feed firefighters' trucks. The aim of this work is to present a rehabilitation strategy for deficient WDNs, involving pipe replacing by means of a Multi-Objective Optimization approach that takes into account single hydrant's final performance and replacing costs, using a Pressure Driven Analysis for solving the hydraulics and a Greedy Algorithm to find Pareto Sets of optimal solutions for different fire locations. A Python 3.7.4 code for the purpose has been written. Pipe replacing is found to be effective in WDN rehabilitation problems and is also considered in other studies about firefighting-related optimization; it is also found to be common the use of DN 150 pipes in WDNs designed for firefighting too. An operational methodology about supply deficient networks with a certain probable amount of water from surroundings DMAs, when fire events occur, is also developed. Both methodologies are applied to the Benalúa's WDN (Alicante, Spain) Case Study. Rehabilitation results show hydrants' performance improvements with affordable costs. This methodology can also be a helpful tool for decision makers, especially when dealing with very large and deficient networks.

ACKNOWLEDGEMENTS

I want to really and mostly thank my so precious family, namely my mom Carmen Pacella, my dad Massimo Farina, my brother Daniele Farina and my partner Giusy Sibilia and her family too, and also my lifelong friend Biagio Ianero for supporting me in this work as well as in life. I owe it all to them.

I thank my supervisors Professor Rudy Gargano and Professor Leonardo Alfonso for constantly guiding and leading me in writing this thesis.

I thank my co-supervisor Professor Carla Tricarico for helping me through all the work and I also thank PhD Oscar Osvaldo Marquez-Calvo for advising me.

I thank my colleague and friend Vincenzo Orlando Forino for being with me for five years by now and for joining me also in this exciting challenge in Netherlands.

Furthermore, I thank IHE Delft Institute for Water Education (Delft, Netherlands) all, for kindly accepting me and making the experience of studying abroad come true.

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LIST OF ABBREVIATIONS AND ACRONYMS

ANW: Additional Needed Water

CDF: Cumulative Distribution Function

CV: Coefficient of Variation

CW: Colebrook-White

DBP: Disinfection Byproduct

DDA: Demand Driven Analysis

DDM: Demand Dependent Model

DLL: Dynamic-link library

DMA: District Metered Area

DN: Diameter Nominal [mm]

EA: Evolutionary Algorithm

EPS: Extended Period Simulation

GA: Genetic Algorithm

GGA: Global Gradient Algorithm

GIS: Geographic Information System

LOC: Loop for Optimal valve Configuration

MOO: Multi Objective Optimization

MOOP: Multi Objective Optimization Problem

NSGA: Non-dominated Sorted Genetic Algorithm

OF: Objective Function

PBV: Pressure Breaking Valve

PDA: Pressure Driven Analysis

PDF: Probability Distribution Function

PDM: Pressure Dependent Model

POR: Pressure-Outflow Relationship

RPI: Residual Pressure Increment

WDN: Water Distribution Network

WDS: Water Distribution System

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1 INTRODUCTION

The primary role of a WDS in urban environment is to supply potable water to users. Due to different users' habits, it must be designed to be reliable and to successfully accomplish its task, even in heavy load conditions. These latter can occur when peak demand takes place as well as when critical events, life fires, involves the use of the WDS. Even if, to this end, in most cases, firefighting networks are designed for building protection, often WDN's aid is required: for this, many underground or above-ground hydrants are installed along main streets of most cities. Firefighters can use them to refill their firetrucks when necessary. Fires are very rare as well as highly dangerous and uncertain events. Due to these features, it is important that hydrants, and WDN more generally speaking, are always able to accomplish the above-mentioned task, in a reliable way and with certain minimum performance. Uncertainty of fires can be mainly due to location, duration and size, and when, instead, a network is deficient (older systems for instance) in such requirements in one or more points, or after a certain amount of time that fire had spread, serious additional risks may arise and for this the government body of a community has the duty of studying sorts of rehabilitation or operational plans to compensate such deficiency.

It is worth to say that, in this work, only public water systems and not water systems exclusively designed for fire protection, will be treated: this will lead to some uncertainties in retrieving regulations or indications about minimum WDNs' requirements in case of fire. For this, Optimization approach can really help: a Multi-Objective Optimization Problem will be formulated in this work, trying to face the rehabilitation issue with the final aim of providing decision makers with a practical tool (or at least an approach to formulate it) to choose which WDN's elements, among others, need to be replaced in an optimal way. In this case, the word "optimal" has this sense: due to known underfunding in WDN works, a trade-off between reached hydrants performance and total rehabilitation costs will be searched for.

Additionally, since many large WDSs are nowadays divided into District Metered Areas with the main end of better managing them, an operational approach to use interconnected DMAs when a fire occurs in one of them, will be proposed. Additional needed water, that may be supplied through links among DMAs that would be otherwise closed, will be in this work evaluated.

More, in this work, an important topic in current WDSs related research will be tackled: Pressure Driven Analysis of water systems. Since classical Demand Driven approach leads to some incorrect results when dealing with deficient or low operating-pressures systems, PDA has been formulated and developed in the last few years and is still being with the final aim of solving this matter. But, since some algorithm’s convergence and software implementation issues were found along the way, Pressure Driven research topics are more than ever current as well as relevant. In this work, an attempt of using PD approach will be done when modelling Case Study’s WDN.

Chapters’ contents will be briefly outlined at the very beginning of the chapters themselves, while in the Introduction section, the reader could just find the reasons that led the author in treating these topics along with a rapid flight onto this work’s contents.

2 STATE OF THE ART

After an Introduction to this work, the current research progresses and findings about treated topics are briefly presented in this Chapter, before exploring the developed Methodologies in Chapters 3 and 4 that just rely on the State of the Art. The aim is to frame this thesis into the scenario of WDNs related issues like:

- firefighting use of urban networks primarily designed for potable water supply to users and their related regulations,
- Optimization Problems concerning WDSs: this is actually a very large topic in scientific literature since Single-Objective and Multi-Objective Optimization techniques are widely spread in approaching this kind of problems, so a brief attempt to frame this big world is made here,
- Pressure Driven Analysis of WDSs and its software implementation: it is a more actual modelling approach and a very current research topic.

2.1 *Firefighting & WDNs*

FIRE MECHANISM

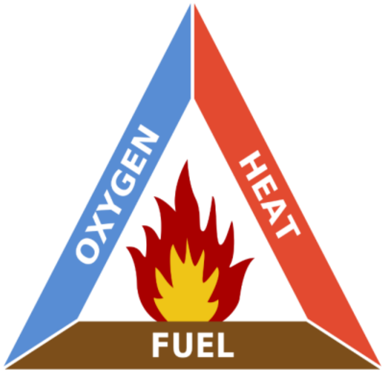


Figure 1: Fire chain: if fuel, oxygen and sufficient heat are put together fire may start.

A fire occurs when an unchecked chemical reaction called "combustion" is triggered by basically putting three things together: a fuel source, an oxygen source and an initial energy source (this latter is the very trigger). In this exothermic reaction the fuel is rapidly oxidized resulting in heat, light and sub-products).

In an urban environment and especially in buildings, fires may occur for different reasons but the most common are:

1. Faulty appliances and leads
2. Faulty fuel supply
3. Misuse of equipment or appliances
4. Placing articles too close to heat [1].

Negative effects of fires include hazard to human life, properties, jobs, atmospheric pollution, and water contamination [2], [3], so it is easy to understand the importance for a community of being able to firstly prevent and eventually manage and finally extinguish a fire.

Fire preventing in buildings should be the first thing to arrange. It can be performed (among many other measures that are not matter of this work) with the use of fire detection alarms. Fire controlling, instead (for instance, when it is just starting, but not spreading yet), can be effectively applied to buildings through the installation of automatic fire suppression systems such as sprinklers or chemical systems. A building developer that properly designs such systems can more effectively protect lives and properties. Fire sprinklers though, are intended to only control a fire, but they cannot completely extinguish it [2].

A fire can be suppressed with three different separated or also combined mechanism:

1. subtracting heat from it, for instance cooling down objects around the fire
2. removing the oxidizer (usually oxygen), to “smother” the fire,
3. removing the combustible material from the site by moving it or by letting it run out in a controlled way.

There are many ways to effectively accomplish this points and it basically depends on the type of fuel involved in the combustion and other additional factors (see Paragraph 4.1 for further information), but it’s not an aim of this work to discuss of this issue. However, we know that for centuries water has been used to extinguish fires because of its inexpensiveness and availability [2]. Water in “sufficient” quantity can cool the fire, the steam can deprive the fire of oxygen and, in the case of miscible or dense fluids, water can disperse the fuel [2]. But how much water is necessary to be considered an adequate supply for fire protection? (Milke, J.A. 1980. How Much Water Is Enough? The International Fire Chief (March), pp. 21–24)

Before this question is solved, whose answer can be found in the next Paragraphs, it is firstly necessary to introduce the role of a WDS in firefighting.

WDS

A WDS’s general purpose is to catch, carry, treat, deliver water to final users with standard requirements. It consists in connections between water sources, pipes, valves, junctions, pumps, reservoirs, grounded storage tanks and elevated storage tanks [4]. A WDN has, thus, the aim of providing potable water to users under normal and abnormal conditions [5] with specified pressure, volume and quality [6]: this means that the water delivery must be reliable even in case of emergencies like pipe failures, power outages, and fires [7]. Other goals for water supply systems are efficient and economic operation of the system, and meeting water quality standards [7] mandated by government body.

When dealing with fires, however, like already mentioned, supplying water to suppress a fire is normally assigned to private or public firefighting water supply systems, specifically designed for this issue, for every single building, whose regulations will be briefly introduced in the next Paragraph. When such a system does not exist or the fire does not strictly concern a building or in other cases too, this task is just given to potable water supply system. So it becomes important to figure that usually a higher amount of water is required, compared to when only user supply is operated: if the water supply system is able to provide a sufficient **Fire Flow** to effectively manage urban fires [8], then the water distribution system can be adequate for fire protection [2]. It is important to remember, however, that drawing large amounts of water from the public water supply system is not the preferred method of fire suppression [2], but in order to make this possible and to improve the firefighting capability of the city, plenty of **hydrants** are installed in the WDN [8].

HYDRANTS

Fire hydrants are connection points installed throughout water distribution systems whose primary purpose is to enable firefighters to have access to the water supply [9],[10]. A hydrant can be located underground or above the ground and it can have different colors depending on use destination or regulations. They can be very numerous (hundreds and even thousands), depending on the size of the city [9]. In case of need, firefighters get on the place and attach a hose to the hydrant on one side and to the fire truck engine on the other side with the aim of suppling the truck's tank with water. Then, they operate a valve on the hydrant to open it and let the water flow into the storage. From here, a powerful pump is used to boost the water pressure and possibly split it into multiple streams to reach the necessary height to successfully manage the fire [10]. For this reason, it is important to know the actual capability of hydrants in delivering an adequate flow at an adequate pressure as well.

Hydrant flow tests may be conducted to estimate available Fire Flow; in addition, they also can be used for hydraulic model calibration [11], leakage hotspot detection [12] and flushing the pipelines to ensure adequate water quality [9], [13], [14]. However, this tests are disruptive, time consuming, prohibitively costly and only approximate [15] and it's also impossible to test each of hydrants in the network. A valid alternative may be found in computer simulation [8]: this consideration is, indeed, carried in this work where a model of the network as well as of the hydrants is implemented, instead of testing hydrants.

Before entering into more specific issues, is good to present two main aspects about the WDN, which will affect the entire work in its whole development, from Methodology to Results and Conclusions.

NETWORK LOOPING

It is well known for many years, that looped networks are more reliable than non-looped ones [2], [16]. In a looped configuration, network's nodes (and so users and also hydrants in case of fire) can receive water from more than one side (pipe), so that, in case of service interruption due to a failure, a maintenance work or critical conditions, just like peak demands or fires [17], the network can still work good and properly deliver water to different nodes.

Network **redundancy** is defined as the number of loops: a network with a high redundancy of pipe loops is likely to be a reliable network. With a view on optimizing it, it is clear that the more the network is redundant, the more improvements become difficult; on the other hand, the less loops the network has the more improvements one can expect to obtain. This consideration is useful when attempting to read this work's Results: they are necessarily affected by redundancy that is itself already a big, and for long time proved, possible improvement for deficient WDSs. Concerning this work, it is possible to anticipate that the available Case Study's WDN has a **high redundancy**.

DECISIONAL VARIABLES

Since, like it will be better explained later, the Rehabilitation Methodology of this work mainly deals with **pipe replacing**, and since Optimization techniques are so widely spread that sometimes they make decisional variables difficult to choose among all available aspects concerning WDNs Optimization, the author considered good to restrict this choice to what actually is considered practical to do. This is also due to computational power at author's disposal. In other words, among many possible network elements to rehabilitate, **pipes** were chosen since it is known that to increase the Fire Flow capacity of the WDS, larger pipes are needed to convey more water. Many authors found that enlargement of pipes was a useful way to improve the firefighting capability [8], [18], [19]. But, since an oversized system will also increase the construction and maintenance costs [8], an Optimization approach that takes into account also **pipe replacing costs** is necessary. Furthermore, talking about pipe's diameter, Decisional Space is still wide, being possible, in theory, to replace a pipe with any of the commercially available diameters. But authors found that the most optimal way is to use a minimum 150 mm diameter of pipes to provide fire protection: this also support the industry practice of using a minimum 150mm diameter pipes to ensure firefighting capability [18], [2], [20]. That being said, this work only focuses on **optimally** replacing links with diameter smaller than 150mm, just with 150mm new pipes. This issue also, is going to strongly affect Results, so it is important to keep in mind the reasons that lead the author in taking this choice.

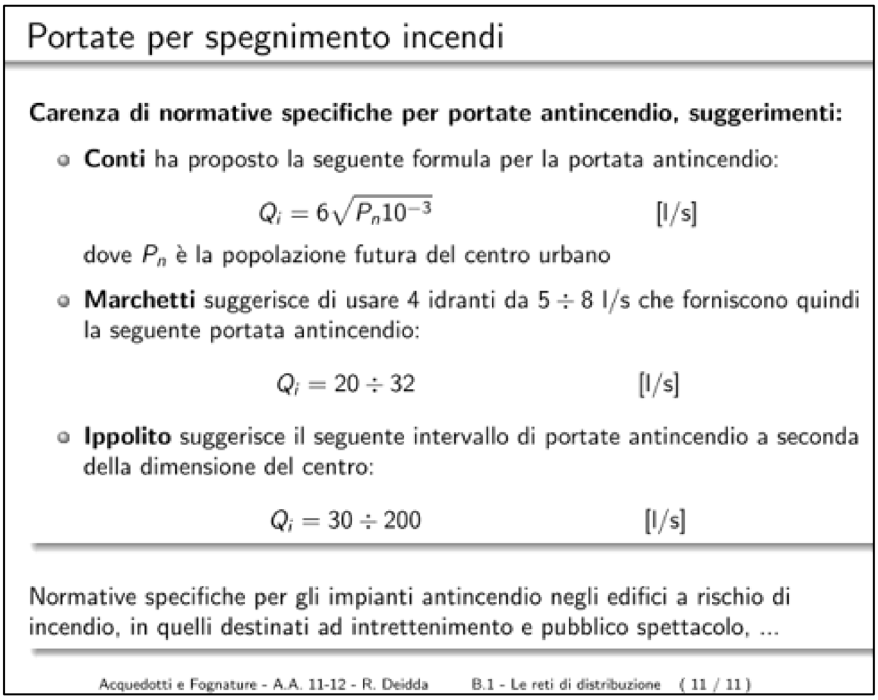
2.1.1 Regulations

Regulations and laws analysis and discussion about firefighting purposes of WDSs are not a main aim of this work. Anyway, in order to have some references and indications about parameters and values that are going to be involved in the optimization process, referring to them was highly necessary. During this search, it became clear to the author of how, while there are clear laws for hydrant networks specifically designed for fire extinguishing (for instance UNI 10779 [21]), there are not so clear laws for designing and verifying the public potable water supply system when used for firefighting purposes. There are, instead, indications, guides and advices. This is probably due to three main reasons:

1. "Using an engine or hose company from a local fire department, which draws large amounts of water from the public water supply system, is not the preferred method of fire suppression" [2] for what we said in 2.1,
2. "There is no legal requirement that a governing body must size its water distribution system to provide fire protection" [2], so it is up to a municipality government to decide if its WDN will be valid for firefighting purposes or not,
3. "One important source of uncertainty in hydraulic design of networks originates from the estimation of needed fire flow" [20].

In spite of these, most communities do provide their WDS of fire managing capability for a variety of reasons (see 2.1) [2] and, because of this, most urban fire services depend upon its fire suppression capacity [22]. In this case it is important to adequately design the WDN: indeed, an inadequate fire protection system provides a false sense of security and is potentially more dangerous than no system at all [2]. Among available references, some are:

- Italian: Conti's formula, Marchetti's and Ippolito's indications (see Figure 2),
- American: Insurance Services Office's method (ISO), Iowa State University method (ISU), National Fire Academy method and Illinois Institute of Technology Research Institute method (IITRI) (all explained in [2]),
- Colombian: "Los hidrantes […] deberán descargar un caudal mínimo de 5 L/s." [23].



Portate per spegnimento incendi

Carenza di normative specifiche per portate antincendio, suggerimenti:

- **Conti** ha proposto la seguente formula per la portata antincendio:

$$Q_i = 6\sqrt{P_n 10^{-3}} \qquad [\mathrm{l/s}]$$

dove P_n è la popolazione futura del centro urbano

- **Marchetti** suggerisce di usare 4 idranti da $5 \div 8$ l/s che forniscono quindi la seguente portata antincendio:

$$Q_i = 20 \div 32 \qquad [\mathrm{l/s}]$$

- **Ippolito** suggerisce il seguente intervallo di portate antincendio a seconda della dimensione del centro:

$$Q_i = 30 \div 200 \qquad [\mathrm{l/s}]$$

Normative specifiche per gli impianti antincendio negli edifici a rischio di incendio, in quelli destinati ad intrettenimento e pubblico spettacolo, ...

Acquedotti e Fognature - A.A. 11-12 - R. Deidda B.1 - Le reti di distribuzione (11 / 11)

Figure 2: Fire extinguishing flows, [17].

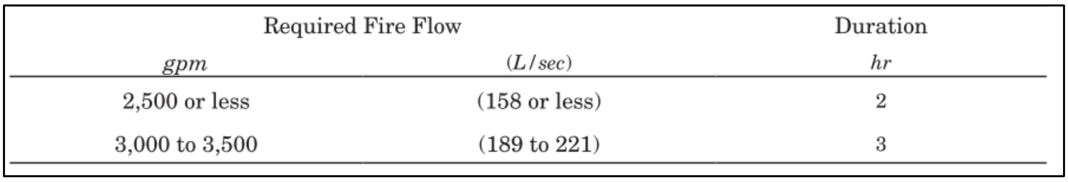
Among American methods, the ISO guide is most likely to yield realistic requirements [2]: for this reason, the author choose to follow its indications, instead of others, throughout both Methodologies.

Therefore, it is important to remember that this work only deals with public water systems and not with water systems exclusively designed for fire protection (as for instance in [21]).

2.1.2 *Technical requirements*

According with [18], [2] and [6], when water is pumped out from a fire hydrant, a **minimum pressure of 138 kPa** (20 psi or 14m of water column) **is required to overcome the headloss between the hydrant and the fire engine pump** and the **required Fire Flow** is intended to be the water flow available with this **residual pressure**. Due to the fact that fires can be very different from site to site, depending on building type and many other factors [2] (see 4.1 for more details), local design may vary, but with this minimum pressure requirement, a flow rate of **32 – 189 L/s** (500 – 3000 gpm) **is required** for firefighting in single to multifamily residential buildings and 158 – 315 L/s (2500 – 5000 gpm) flow is required for commercial and industrial buildings [6].

Additionally, recommended **Fire Flow duration** is obtained from **Table 1** below, according to the required Fire Flow range.



Required Fire Flow		Duration
gpm	(*L/sec*)	*hr*
2,500 or less	(158 or less)	2
3,000 to 3,500	(189 to 221)	3

Table 1: Fire flow durations [2]**.**

2.2 *WDSs Optimization*

An Optimization Problem aims to find and compare feasible solutions until no better solution is found in terms of an Objective, usually subjected to constraints: most common objectives are cost of production, efficiency of a process [24] and, more recently, reliability and robustness too [25], [26], [27], [28], even if their formulation is not still unique and has many different interpretations. Constraints may have different nature. Mala-Jetmarova et al. [29] report first calculus-based Optimization before the digital era, by Tuttle in 1895. The first classical problems aimed, thus, to maximize or minimize **one** objective at a time. Since, rather, most common life problems are made of many of them to be maximized or minimized, Multi-Objective Optimization Problems are very interesting and challenging to solve because a trade-off between conflicting Objectives needs to be found.

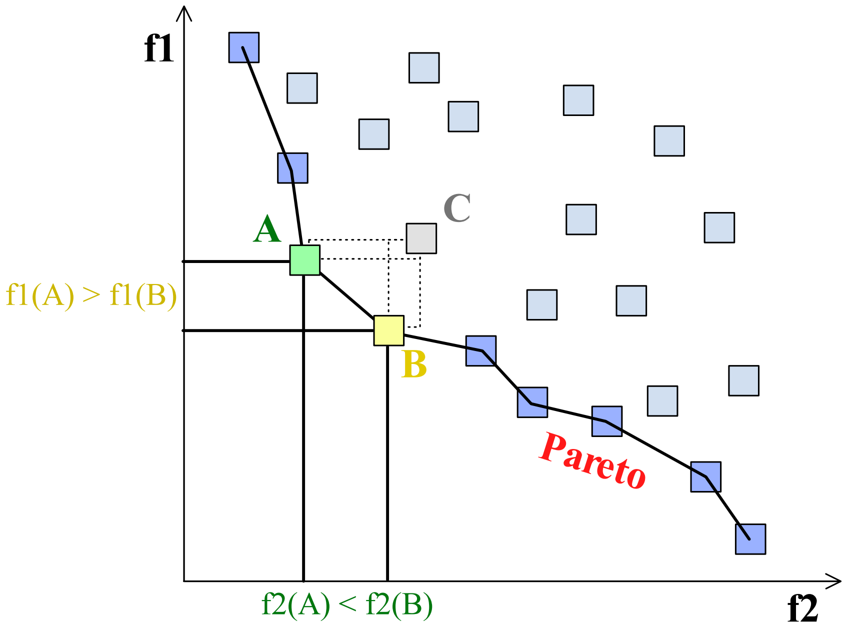


Figure 3: Pareto frontier: By Nojhan - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=770240

In this case, a possibly infinite number of **optimal solutions** may exist. A solution is called **nondominated or Pareto optimal**, if none of the Objective Functions can be furtherly improved in value without degrading some of the other Objective Functions [30]. Such set of solutions is called **Pareto Set of Optimal Solutions.**

Regarding WDSs, Mala-Jetmarova et al. [27], [31] have identified over 300 journal papers published in the last three decades alone on the topics of WDS design and operational optimization [26].

New WDSs need to be **designed** and existing ones need to be **operated, rehabilitated** or even **redesigned** even if it is well known that funds available are usually insufficient to fully achieve these goals [25], [26], [32]. WDSs also often need to be **calibrated**. For these reasons MOO becomes useful.

To accomplish this task, a big number of methods have been developed through years: optimization research works started applying deterministic methods in the 1980s and then, stochastic and hybrid approach in the 1990s [25].

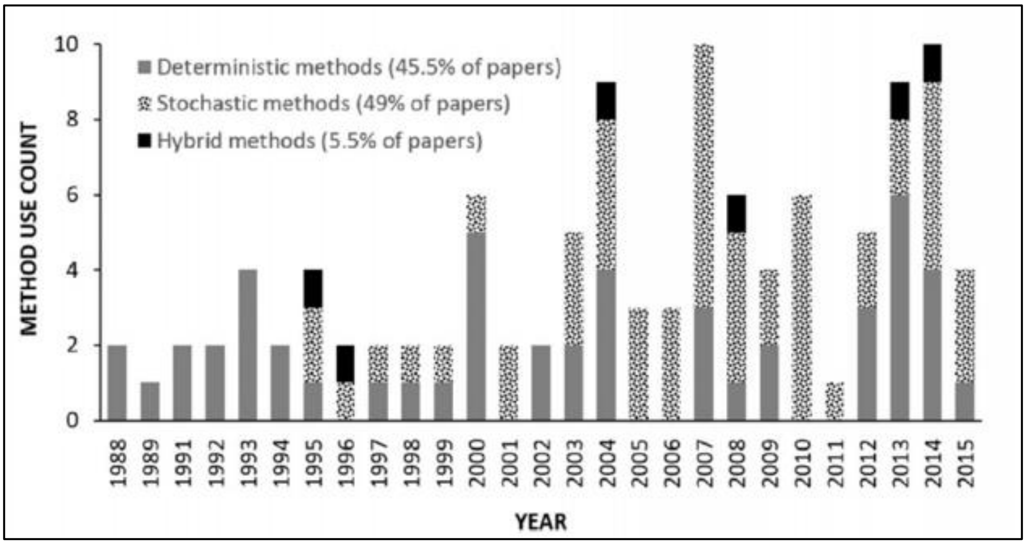


Figure 4: Optimization methods by year [27]**.**

The optimization methods can be categorized as follows: [25], [26]

- Deterministic (exact) optimization techniques:
    1. Linear programming (LP) for continuous problems with linear Objective Function subject to linear constraints. The use of LP in WDSs requires linearization: this had success like reported by [13]. It converges to a globally optimal solution,
    2. Non-linear programming (NLP) can only manage less complex WDSs. NLP too, uses continuous variables, but unlike LP solution does not always converge to solution,
    3. Dynamic programming (DP) decomposes a multistage problem into a sequence of single-stage decision-making operation: this too has limited usage in WDSs problems;
- Stochastic optimization techniques (Metaheuristics):

  They were introduced in 1990s along with the improvement in computers' computational power. Metaheuristic is a strategy with which only a portion of the search space is explored by the algorithm, with a certain criterion (direct search, random search, clustered search etc.), that **may** be able to find the optimal or **near-optimal solution** even with incomplete data. Most of them are nature or physics inspired and population based. Linearizing assumptions are not required.

The advantage of metaheuristics over deterministic optimization is that they are able to solve complex optimization problems which no specific deterministic algorithm is capable of solving.

The review of the research literature over the last 30 years shows the absolute domination of metaheuristics in WDS analysis [26].

Mala-Jetmarova et al. [27] reviewed a list of research works that applied various metaheuristics to WDS optimization, some which include: genetic algorithms [33], harmony search, simulated annealing, evolutionary algorithms (EA) and others. Among these, population-based optimization techniques (genetic algorithms in particular) have become popular in recent years for both WDSs **design** and **operation** [34], [35], [36].

More recent methods are also multi-method search [37] and hyperheuristics [38].

Usually, WDS optimization process may be complex due to **non-linearity relation** between link headloss and node pressure [25]: in Paragraph 2.3 network simulation models are better introduced.

Sometimes objective functions neither can be analytically formulated since their evaluation comes from software runs based on the network model (as in this work): in these cases metaheuristics can solve the problem [39], [40], [41].

DESIGN and REDESIGN

Firstly, optimization problems tackle system design [42]. Most of these are single-objective and basically aim to minimize the overall cost of the network, with pressure constraints and user demands constraints [25].

The very first optimization mathematical implementation considered looped WDS design as a least-cost pipe sizing exercise for a single demand condition [43].

In [26], some design optimization problem examples in literature are listed: [33], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53].

When, instead, existing WDNs are deficient or unable to satisfy water requirements, optimal improvements should be planned. Numerous contributions on the redesign topic can be found in literature: [32], [54], [55], [56], [57]. Redesign includes **strengthening**, **rehabilitation** and **expansion** of existing systems [26].

OPERATION

Operational problems deal with pump operation (the most often encountered [26]), water quality management (first [58]) and valve control. For solving them, optimization methods have been applied by [41], [59], [60], [61], [62], [63]. They also deal with model calibration that aims to determine various parameters of the network model, so to let measures and predictions match [26].

Finally, operational problems are also about partitioning the WDN into District Metered Areas (DMAs) [26].

Challenges for future research include: formulation of reliability, robustness, and resilience metrics for inclusion with optimization of WDS, the treatment of uncertainty within the design process, and making research tools closer to the practitioner [26].

Talking about algorithms, a common MOO Genetic Algorithm is, for instance, the NSGA-II (Non-dominated Sorted Genetic Algorithm) by Kalyanmoy Deb [24], [64].

GREEDY ALGORITHMS

These algorithms are very faster than exhaustive searching algorithms because actually they do not explore all possible combinations of solutions: indeed, they find the best local solution from an initial set and then, keeping memory of that, continue finding the next best local solution, until some constraint is violated or the presumed global maximum (or minimum) is reached. Matter of fact, this is not an exhaustive procedure because it excludes so many feasible solutions from the Decisional Space, but for some kind of problems, in which such algorithms are effective, they really can be much faster than others.

2.3 Pressure Driven Analysis of networks

A correct network modelling has with no doubt a very important role in optimization problems. It is well known that WDNs analysis is complex [6], [65] due to:

1. the complexity of their topological layout,
2. the non-linear mathematical relation between headloss and water flow,
3. the dynamic behavior of water demand, that is affected by climate and seasons [66], [67], [68] and by users' habits [69], [70], [71].

For these reasons, mathematical equations system that roles the problem is not so simple to solve. Many methods have been developed over the years and among the most important one can mention:

- Head or Flow balancing: for instance Hardy- Cross [72],
- Matrix methods: they usually use Linearization method or Gradient method, like Newton-Raphson.

In 1987, Todini & Pilati [73] released the Global Gradient Algorithm, a matrix method based on Newton-Raphson gradient method that aimed iterative resolution of equations' system formed by momentum equations and continuity equations [73], [74]. The solution was given in vector form and this was, what we call today, the Demand Driven concept. GGA is still today the algorithm implemented in Epanet 2 [75].

DDA ([73], [76], [77], [78]) is the traditional approach for simulating WDNs: with it, hydraulic simulators, like EPANET [75], assign fixed demands, to be delivered to users, to network nodes. It is worth to notice that, actually, these demands are strongly mutually interdependent [79], [80] ,[81]. DDA's mathematical and software implementation results in successfully delivering this demand even if there are **not** physically compatible conditions, that is to say even if pressure at nodes results to be insufficient or even negative [75], [82]. Of course, having negative pressure at nodes makes no sense, but this issue only comes to one's attention when attempting to analyze deficient networks. Some studies show [83] how, when networks work under critical conditions [5] (for instance peak demand, a failure or a fire event) or they are deficient themselves, DDA shows to have limitations and may lead to wrong results [5], [84].

In that sense, research and literature are very active and in the last few years many attempts have been done to develop a more physically correct method: **Pressure Driven Analysis**. PDA basically introduces a more realistic relation between demand and nodal head to model the node outflow depending on the actual available nodal head.

Regarding firefighting, using PDA is convenient since fire-fighters don't actually care about **residual pressure at hydrants** (the node parameter resulting from classical DDA) but, instead, they do care about **outflow**, since the main purpose of hydrants is to be able to refill the truck's water tank in a brief time. So, actually, it's really important to have knowledge about flow instead of only pressure and the right way to realistically know flow values is to use a PDA instead of a classical DDA.

Due to the increased computational difficulty, brought by the introduction of such relation in the already complex equations system, many efforts have been done, and currently are still being, to effectively implement different approaches in a computer software. Indeed, in the past, PDA implementations have suffered from convergence difficulties [85].

Many PDA approach attempts were made, like [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104]. Anyway, this work is not going deep into any of them, but, since most recent progress on the topic led to the development of EPANET 2.2, a beta release of an open source version of Epanet [75] by OpenWaterAnalytics Community, with a user interface, this latter, in particular the Build 2.2.01, was used in this work.

Modelling Pressure-Outflow behavior, some suggest the use of mathematical Relationships (POR) like [92], [93], [95], [97] and [103], especially when experimental data are missing [82].

Todini (2003) [86] suggests, instead, of not using a POR at all [91], due to reduced convergence in the original algorithm [105].

A 2018 updated graphical comparison between five of them by [82] is reported in Figure 5: they are here valid for $h_{min} = 0$ and $h_{des} = 20$.

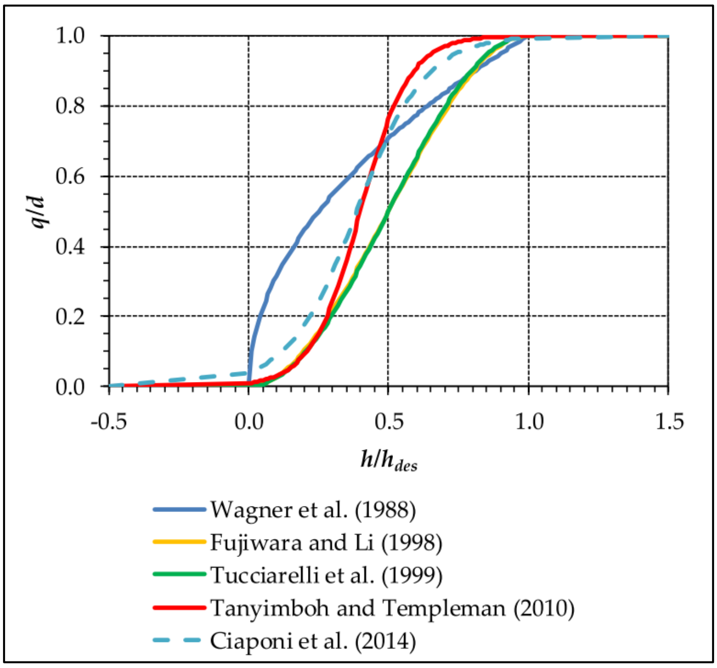


Figure 5: Ratio of outflow *q* to demand *d* as a function of the ratio of the generic pressure head *h* to the desired pressure head h_{des} for the various formulations [82].

3 METHODOLOGY FOR REHABILITATION

In this Chapter, a Methodology is developed with the aim of Rehabilitating a deficient WDN, so to meet requirements previously listed in Paragraph 2.1.2 and make it effective again for firefighting purposes; the Methodology is presented along with the use of MOO to approach it.

In particular, the following Methodology is to restore deficient hydrants' operative conditions in an urban water supply distribution network, when they do not work properly due to the reason introduced in Paragraph 2.3 and in a deterministic specified Scenario explained in Paragraph 3.1.

Even though, in this work, Methodology strictly derives from Case Study, the former is presented first, with the aim of giving a general approach of the problem to the reader.

Firstly, in Paragraph 3.1, considering what has been said about firefighting purposes in Paragraph 2.1 and about WDN's hydraulic simulation in Paragraph

2.3, some assumptions and criterions on network mechanical and hydraulic modelling are showed. Then, in Paragraph 3.2, MOO approach is explained: problem is set in terms of objective functions, constraints and decisional variables along with Greedy Algorithm developed to generate the Pareto set of optimal solutions.

3.1 Network modelling

Correct network modelling is very important: actually, a network model should also be calibrated to give strongly reliable results, but, since calibration is itself a very large branch of MOOPs, it is not faced in this work, and network modelling relies on the experimental data collected about users’ consumptions and pressure measurements as it will be explained. Anyway, the aim of disposing of such a model is to be able to run hydraulic simulations and evaluate WDN’s hydrants Fire Flow capacity, more conveniently than executing fire flow tests (see Paragraph 2.1): indeed, physically setting up and analyzing critical situations would be difficult, or even impossible [14].

WATER DEMAND

Very commonly, as in this work too, water demands are assigned to single nodes of the WDN instead of being distributed along pipes. Attempts in this sense have been made, for instance, in [106] and [107].

The peak water demand for residential users is one of the most onerous operative conditions for an urban WDS. This scenario, along with (among others) fire-fighting flow demands, may cause WDS deficiency. Hence, peak demand is usually considered for WDS design and management [6], [69], [108] and reliability assessment [2].

Water demand in this work is assumed to be **deterministic**.

$$\boldsymbol{C_P = \frac{Q_P}{Q_m}}$$

- $\boldsymbol{Q_m}$ is the daily average flow in the network,

- $\boldsymbol{Q_P}$ is the hourly peak demand in the network,
- $\boldsymbol{C_P}$ is the Peak Coefficient,
- $\boldsymbol{Q_P}$ and $\boldsymbol{C_P}$ are evaluated by means of a Gumbel Cumulative Distribution Function that has the form of:

$$\boldsymbol{P[S] = e^{-e^{-\alpha(x-\varepsilon)}}}$$

and consequently,

$$\boldsymbol{x = \varepsilon\left(1 - \frac{1}{\varepsilon\alpha}\ln\left(\ln\frac{1}{P[S]}\right)\right)}$$

where:

- $\boldsymbol{\mu}$ is the **mean** of the CDF (1° parameter),
- $\boldsymbol{\sigma}$ is the **standard deviation** of the CDF (2° parameter),
- $\boldsymbol{\varepsilon}$ is the mode of the CDF: $\boldsymbol{\varepsilon = \mu - 0.45\sigma,}$
- $\boldsymbol{\alpha = \frac{\pi}{\sigma\sqrt{6}}}$,
- $\boldsymbol{P[S]}$ is the probability of exceedance of the CDF,
- $\boldsymbol{x}$ is the generic random variable,

In this case $\boldsymbol{x}$ = $\boldsymbol{C_P}$ is the random variable and it is evaluated, depending on $\boldsymbol{P[S],}$ hourly collecting network flow data with a **flow meter** and computing the $\boldsymbol{\frac{Q}{Q_m}}$ ratio. The CDF is given by assessing the distribution's parameters $\boldsymbol{\mu}$ and $\boldsymbol{\sigma}$ through above mentioned flow meter data collecting. In this work only the worst deterministic **critical scenario** (from now on **Scenario**) will be considered to run simulations, assuming that this latter could be the most stressing condition when a critical event, such as a fire, occurs. That being said, it could happen that a fire occurs just when the network is called to supply the network hourly Peak Demand: from this, the deterministic Peak Demand value will be evaluated with a **probability of not exceedance $\boldsymbol{P[S] = 99\%}$.**

Effectively delivered water is known at delivery points (nodes) allowing to assign the **average water demand** to each network node.

LEAKAGES

Leakages data are intended as difference between water volume entering the network through flow meter and water volume effectively accounted at users' delivery points by water supply company

$$\boldsymbol{Leakages = water\ entering\ WDN - water\ accounted}$$

To take leakages into account in water demand modelling, so to correctly analyze network, each user's **average water demand** is fictitiously multiplied by the inverse of the network **Performance** defined as follows:

$$\boldsymbol{Performance = \frac{water\ accounted}{water\ entering\ WDN}}$$

$$\boldsymbol{Base\ demand = Average\ water\ demand * \frac{1}{Performance}}$$

Consequently, in the **Scenario**, each **Base demand** is multiplied by the Peak Coefficient $\boldsymbol{C_P}$ resulting in the overall network Peak Demand condition.

NETWORK ELEMENTS

Info about pipes, nodes, valves, tanks and hydrants are merged together to build the network topology, while hydrants **fire flow** is modelled like eventual additional node demand. When a hydrant is supposed to be operated, **fire flow** is additioned to **Base demand**.

Pipes roughness assessment is not part of this work, so data about it are assumed to be exact from Case Study database.

With the aim of emphasizing the **Scenario**, the WDN water source is considered almost empty (due, for instance, to a long-lasted network peak demand occurrence): $\boldsymbol{h_{tank} = 0.1m}$ is assumed as water level in the water tank.

FIRE FLOW

Since fire flow requirements have been introduced in Paragraph 2.1.2, and since actual buildings considerations are not part of this work (see Chapter 4 for further considerations) a **single hydrant Fire Flow** of **32L/s** as minimum effective firefighting requirement is assumed:

$$\boldsymbol{Flow = 32L/s}$$

and a **fire duration** of **2 hours** taken from **Table 1** is considered:

$$\boldsymbol{d = duration = 2\ hours}$$

LOCATION

The MOOP is run separately for every of the WDN’s hydrant: this implicitly allows to consider as a possible location of fire, almost any point of the WDN since hydrants are placed, by law, uniformly in the network. It is implicitly assumed that a fire is being managed with using **only 1 hydrant at a time**.

For this, as many **Pareto Sets of solutions as hydrants** will be generated and this also allows decision makers to decide rehabilitation priority among hydrants.

SUMMARY OF SCENARIO

The **critical scenario** during which is imagined a fire can take place in any point of the WDN is, thus, the following:

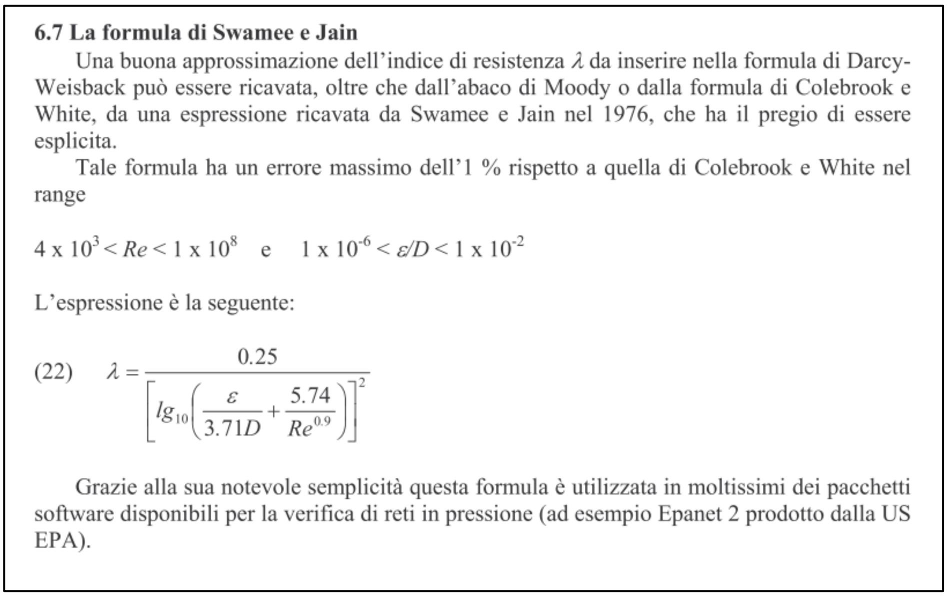
- Peak Demand in the network with a Gumbel CDF $\boldsymbol{P[S] = 99}\%$,
- Water source (tank) almost empty: $\boldsymbol{h_{tank} = 0.1m}$,
- Fire duration $\boldsymbol{d = 2\ hours}$.

In these critical conditions, the WDN is called to effectively deliver $\boldsymbol{32L/s}$ **to any of the hydrants in the network for a 2 hours fire.**

If any of the hydrant results to be deficient in meeting this minimum requirement, MOO takes place to rehabilitate the network.

HYDRAULIC SIMULATION SETUP

Darcy-Weisbach Equation is used for computing head losses in pipes. For turbulent regime the friction factor is evaluated with the Swamee & Jain expression, reported here below and also implemented in Epanet hydraulic solver as in many others hydraulic simulators.



6.7 La formula di Swamee e Jain

Una buona approssimazione dell'indice di resistenza λ da inserire nella formula di Darcy-Weisback può essere ricavata, oltre che dall'abaco di Moody o dalla formula di Colebrook e White, da una espressione ricavata da Swamee e Jain nel 1976, che ha il pregio di essere esplicita.

Tale formula ha un errore massimo dell'1 % rispetto a quella di Colebrook e White nel range

$4 \times 10^3 < Re < 1 \times 10^8$ e $1 \times 10^{-6} < \varepsilon/D < 1 \times 10^{-2}$

L'espressione è la seguente:

$$\lambda = \frac{0.25}{\left[lg_{10}\left(\frac{\varepsilon}{3.71D}+\frac{5.74}{Re^{0.9}}\right)\right]^2} \tag{22}$$

Grazie alla sua notevole semplicità questa formula è utilizzata in moltissimi dei pacchetti software disponibili per la verifica di reti in pressione (ad esempio Epanet 2 prodotto dalla US EPA).

Figure 6: Swamee & Jain friction factor expression (Angelo Leopardi, 2005).

To consider the dynamic behavior of the network when a fire event occurs, an EPS (Extended Period Simulation) is run instead of a Single Period Simulation.

A Pressure Driven Analysis is conducted instead of the classical Demand Driven Analysis: its software implementation is reported in Paragraph 6.2.

The pressure-outflow behavior has **power trend** if pressure drops below **Required Pressure**.

For what has been said in Paragraph 2.1.2:

$$\boldsymbol{Required\ Pressure = 14m}$$

This is also a parameter required within a PDA as well as a technical minimum requirement.

3.2 Problem setting

Reliably supply of water in all circumstances can be achieved, among others, by proper operation and maintenance of the system [7].

In particular, when a nodal demand is very high, with respect of normal working conditions, like when in a fire event a hydrant is operated to draw water from the WDN (as presented in Paragraph 2.1), this latter may temporarily become deficient and unable to satisfy fire flow demand, causing reliability problems and additional risks. The prediction of the performance of a WDS under a temporarily-deficient condition is necessary for simulation-based reliability analysis and design of WDSs [92] and consequently also in sight of rehabilitating an existing one (redesign problem [57]). Furthermore, even though software implementation of PDA is not so mature yet, it is a more realistic way to run and simulate WDSs' behavior. It has also already been seen how pipes enlargement, along with an optimal way to invest funding, is a useful way to improve the firefighting capability of a WDN [8], [18], [19].

Thus, in this Paragraph, is outlined the very MOO problem, its analytic formulation and Greedy Algorithm used for the purpose, taking into account all the considerations done so far.

3.2.1 Objective Functions

Due to the fact that network pressure at nodes and correspondent actual available demands, in a PD approach, are mutually dependent, Objective Functions could be stated as in terms of Pressure as in terms of actual Demand. Also, it has been shown how urban potable water supply network hydrants are installed to provide fire trucks with minimum requirements seen so far and recalled here below:

- $\boldsymbol{Flow = 32L/s}$
- $\boldsymbol{Required\ Pressure = 14m}$
- $\boldsymbol{duration = 2\ hours}$

Since PDA allows to retrieve **actual available demand** from a node, and since firefighters only actually care about effectively filling fire truck's tank with water, and since low fire flows are a common operational problem in WDNs [14], Objective Function **should** be stated in terms of **Outflow at the hydrant node.**

Anyway, since **Fire Flow** is set as a **fixed node demand** and as a **minimum requirement,** setting Objective Function in terms of Outflow could **limit improvements** deriving from Optimization approach: instead, setting Objective Function in terms of **Residual Pressure** (even though it is not the very aim) allows to visualize more improvements deriving from Optimization process since pressure is not imposed to be a fixed requirement, but the highest it is, the better it is. That being said, a first aim becomes **Maximizing the Residual Pressure [m]**.

DN [mm]	$D_{internal}$ [mm]	C [€/m]
75	66	100
90	79.2	105
110	96.8	118
125	110.2	123
140	123.4	133
160	141	141
180	158.6	150
200	176.2	163
250	220.4	194
280	246.8	212
315	277.6	241
355	312.8	269
400	352.6	303
450	396.6	345
500	440.6	407
630	555.2	562
710	625.8	707
800	705.2	852

Figure 7: Rehabilitation unitary costs by [57].

Also, rehabilitation costs will be considered, and regarding this, it can be said the following.

The second aim is to **Minimize total rehabilitation costs [€].**

To do this, briefly introducing decisional variables is necessary: **pipes will be replaced** inside the MOOP and **unitary cost for pipe replacing** by Tricarico et al. [57] will be used in the optimization formulation: in particular, this relation relies upon Italian pipe replacing rehabilitation costs.

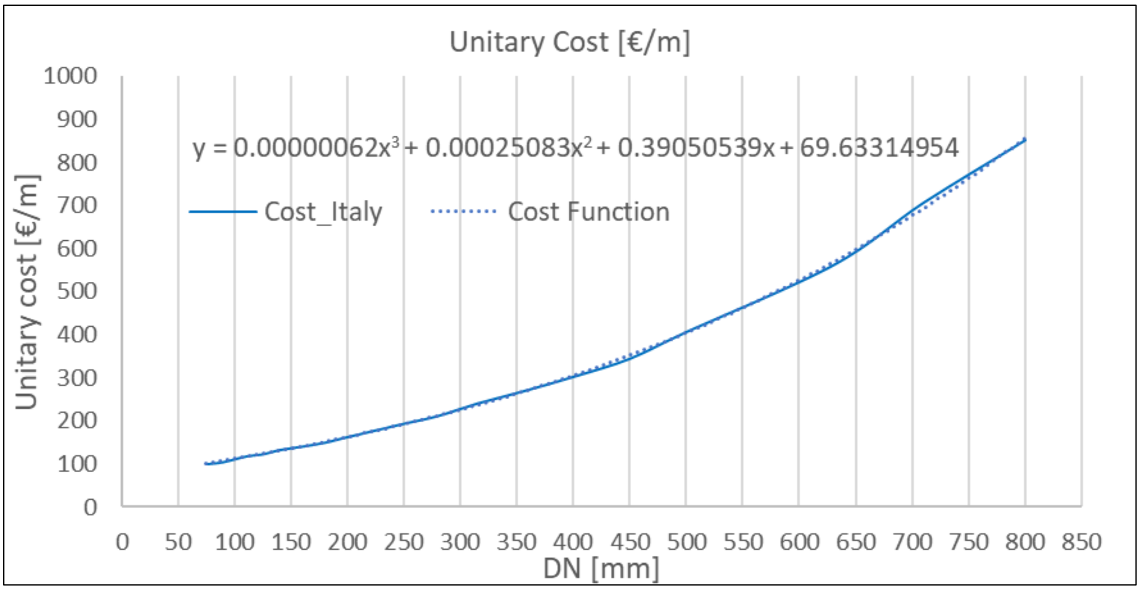


Figure 8: Pipe replacing unitary cost function by [57].

Multiplying Unitary Cost [€/m] by pipe length [m], specifically for pipe diameter [mm], Cost [€] is obtained.

$$\boldsymbol{Cost}[€] = \boldsymbol{Unitary\ cost}\ \left[\frac{€}{\boldsymbol{m}}\right] * \boldsymbol{Length}[\boldsymbol{mm}]$$

Now, in **one rehabilitation intervention,** Objective Function **Residual Pressure Increment (RPI) to maximize** and Objective Function **Cost to minimize** can be merged into a **temporary** MOO’s Objective Function **ObF0** :

$$\boldsymbol{ObF0}_{\boldsymbol{i}} = \left(\frac{\boldsymbol{RPI}_{\boldsymbol{j}}}{\boldsymbol{Cost}_{\boldsymbol{j}}}\right)_{\boldsymbol{i}}\ to\ be\ \boldsymbol{maximized}\ \forall\ \boldsymbol{j} = \boldsymbol{1}..\boldsymbol{pipes}$$

while final reached **Residual Pressure at i-th hydrant** will be assumed as **ObF1.**

$$\boldsymbol{ObF1_i = Residual\ Pressure_i}\ to\ be\ \boldsymbol{maximized}$$

It is worth to specify that **index i** means that MOOP is run **separately for each of the i hydrants in the network. Index j** instead, stays for the **j-th pipe** that is replaced (intervention).

ObF0 will be evaluated relatively to **one rehabilitation intervention,** but, since the main aim is to meet the correct hydrant operation, there is no guarantee that aim is effectively reached with just one intervention: eventually, many interventions could be necessary to reach the goal. This means, that introducing a **Total Cost [€]** is necessary: **Total Cost** is defined as the cumulative cost after a certain number of interventions and it is assumed to be the **ObF2.**

$$\boldsymbol{ObF2_i = Total\ Cost_i = \sum_{j=1}^{k} Cost_j}\ to\ be\ \boldsymbol{minimized}$$

$\boldsymbol{k}$ is the number of interventions that are necessary to reach the goal of rehabilitating the **i-th hydrant**, while $\boldsymbol{j}$ is, again, the j-th pipe replaced.

The aim is to **Minimize total rehabilitation costs [€].**

Evaluating $\boldsymbol{ObF1_i}$ and $\boldsymbol{ObF2_i}$ for **each of the i hydrants** in **Scenario** condition will result in obtaining a **Pareto Sets** of **near-optimal solution**.

3.2.2 Constraints

In MOOP constraints are often introduced, due physical limits of the problem: they are intended to be Objective Function co-domain restrictions or Decisional Space domain restrictions. Such restrictions are often necessary in MOO to reduce evaluation and computational times in very complex problems.

Relatively to this problem, constraints will rule the Algorithm's behavior that, otherwise would keep evaluating Objective Functions without an end.

Specifically, here below are constraints stated:

- If $\boldsymbol{RPI_j < \varepsilon}$ → Algorithm stops, where $\boldsymbol{RPI_j = RPI_j - RPI_{j-1}}$**.** This means that if no more pipe change can improve effectively the Residual Pressure, it is assumed that keep evaluating is useless: $\boldsymbol{\varepsilon = 0.1m}$**.**
- If number of pre-defined pipes replaced is reached → Algorithm stops: MOOP for i-th hydrant stops anyway when **10 pipes are replaced.**

3.2.3 Decisional variables

Solutions to low fire flows depend on different kind of problems that network analysis and field data collection can identify. In general, they may be: [14]

- Upgrading pipes,
- Cleaning and lining pipes,
- Booster pumping,
- Additional storage near to the hydrants.

Even though each of these options should be compared with a benefits-costs criterion [14], only **upgrading pipes to DN150mm**, will be explored in this work, because many authors found it to be effective when rehabilitating WDN for hydrant fire flow requirements and it is a common industry firefighting practice [2], [8], [18], [19], [20]: these reasons are better explained in Paragraph 2.1. In the end, **decisional variables are pipes:**

$$\boldsymbol{if\ \ D_j < DN150\ \rightarrow\ D_j = DN150}$$

where, again, **index j** identifies **j-th pipe** in the network.

It is worth to say that a **“do-nothing”** solution is always included in the Decisional Space and so in **Pareto sets of solutions**. In this way, a comparison is made on how much, eventually, **ObF1** improves for different configurations with respect to the original status.

3.2.4 Greedy Algorithm

As introduced in Paragraph 2.2, a Greedy Algorithm is a non-exhaustive search algorithm: this means that not all Decisional Space is explored and actually a lot of combinations between different solutions are avoided and not evaluated at all. In spite of this, it is really effective and fast above all, for some kind of problems. Inspiration in implement such an algorithm in this work came from [28], [109], [110], [111] and [112] in which results show how authors’ Greedy Algorithm called “LOC” (Loop for Optimal valve status Configuration) is able to find **near-optimal** solutions using a fraction of the computational time required by a brute force search. It is worth of notice the **“near-optimal”** expression: because Optimization process relies upon network model software simulations run and results, it is impossible to have a continuous function for **ObF1,** nor for **ObF2.**

For these reasons, it is not known for sure that a better solution exists, and thus, the non-dominated Pareto fronts are said to be “near-optimal”. Thus, the main reason why author uses such an algorithm instead of a random-search one (for instance NSGA-II) is its speed, compatibly with the computational power at his disposal.

WHY AN ALGORITHM

After looking at Results Chapter, one could say that what is just found is obvious, but it is not, especially because we have a Case Study with a very redundant network:

In Figure 9, let assume that algorithm outputs that the best pipe to change is Pipe1. One could think that this is logical because that is the nearest pipe, but, actually, which nearest of the three? How could reader say a priori, in a very highly looped network (in these cases a node can easily have up to 4 pipes suppling water to it), that the best to change is exactly Pipe1?

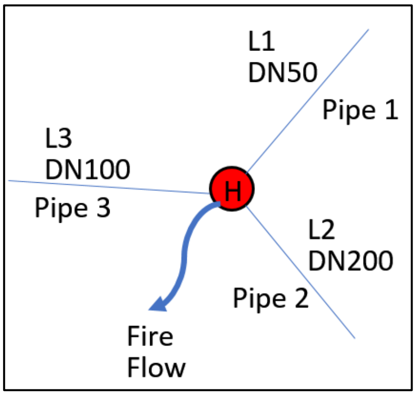


Figure 9: Why an algorithm?

Fortunately, software can easily run hydraulic simulations and through them one can prove or not that Pipe1 is the best possible one to upgrade from

DN50 → DN150 among other pipes and actually improves hydrant’s situation the best.

The issue is that: acting like this in a big, looped, redundant network, it is too slow and, in the end, only leads to find that changing **one** pipe actually improves (so the assumption about Pipe1 was right) **one** hydrant, the one on which evaluation is running.

Now, to be sure that there is not one other pipe that, being upgraded, can even better increase the hydrant performance, all other pipes have to be **manually** changed in the software, one at a time, and repeat the evaluation. This also has to be done:

- for all hydrants
- eventually, for different fire durations
- for multiple pipes, until **Fire Flow** requirement goal is reached
- eventually for different scenarios in which more than 1 hydrant can work together (future developments of this work)

All this, with no doubt, requires a huge amount of time and effort and it is almost impossible to be done without some kind of automation. Thus, an algorithm, written in a script code can really help to face this issue, and actually did it, making possible to implement the Rehabilitation Methodology presented in this work.

GREEDY ALGORITHM EXPLAINED

Here are presented the steps through which greedy algorithm allows to obtain Pareto Sets of solutions and Pareto Fronts by:

- Maximizing ObF1,
- Minimizing ObF2,
- Upgrading pipes to DN150,
- Subjected to constraints in Paragraph 3.2.2

For the i-th hydrant of the network:

1. A WDN EPS is run in Scenario conditions
2. $\boldsymbol{ObF1 = Fire\ Flow_{0_i}}$ is evaluated: Fire Flow in the do-nothing event (j=0)
3. 1-st loop of Algorithm runs:
    a. j-th pipe of the network with DN<150 is **upgraded** → DN150
    b. EPS in Scenario is run
    c. ObF0 is evaluated and stored in a vector
    d. j-th pipe is restored to original diameter
4. Max ObF0 is located in the vector and corresponding pipe is **definitely upgraded to DN150**: this pipe is the one that gives the most increment with the least cost. From this moment on it will be **kept** and will be removed from the set of Decisional Variables
5. $\boldsymbol{ObF1}$ and $\boldsymbol{ObF2}$ are newly evaluated
6. Points **3, 4, 5** are reiterated for **until any of the Constraints is violated** (Paragraph 3.2.2)
7. Algorithm stops and data for drawing **Pareto Fronts** are available.

Methodology applied to Case Study can be found in Paragraph 7.1.

4 METHODOLOGY FOR OPERATION

In this Chapter, the Methodology for additional needed water volume evaluation for operational purposes in case of critical fire events is presented.

When emergency conditions like fire occur, making an effective decision in a short time to operate the WDN, may be very difficult and stressing, even if a hydraulic model of the system is available [41].

One of the possible operations in case of fire is the additional supply of water. In Chapter 3, it was implicitly assumed that WDS could be successfully supplied by any amount of water. In case this is not possible, the following Methodology is developed: supplying water to WDN from different points of the network itself by means of probabilistic evaluation of the necessary additional amount of water.

4.1 ISO guide

For this purpose the ISO Guide presented and explained in [2] will be used as reference. It is a rating service to determine needed fire flow during an evaluation for insurance purposes [2].

“The required fire flow is defined as the rate of water flow at a residual pressure of 138kPa for a specified duration to extinguish the fire. It is varied with the building size, building material, the structure and contents of the building, exposures, weather, temperature, the existing fire protection measures and so on [2]” [8]: indeed, all fires are basically different.

The ISO’s technique is documented in its publication Fire Suppression Rating Schedule (Fire Suppression Rating Schedule. 2003. Jersey City, N.J.: Insurance Services Office Inc.) in which needed fire flow (NFF) is defined.

Needed fire flow (NFF)

“The NFF is the rate of flow considered necessary to control a major fire in a specific building for a certain duration. It is intended to **assess the adequacy** of a water system. However, it is very unusual for an existing water distribution system to be capable of providing every NFF within its service area […]” [2].

$$\boldsymbol{NFF} = (\boldsymbol{C_i})(\boldsymbol{O_i})[\mathbf{1.0} + (\boldsymbol{X} + \boldsymbol{P})_i] \; [gpm]$$

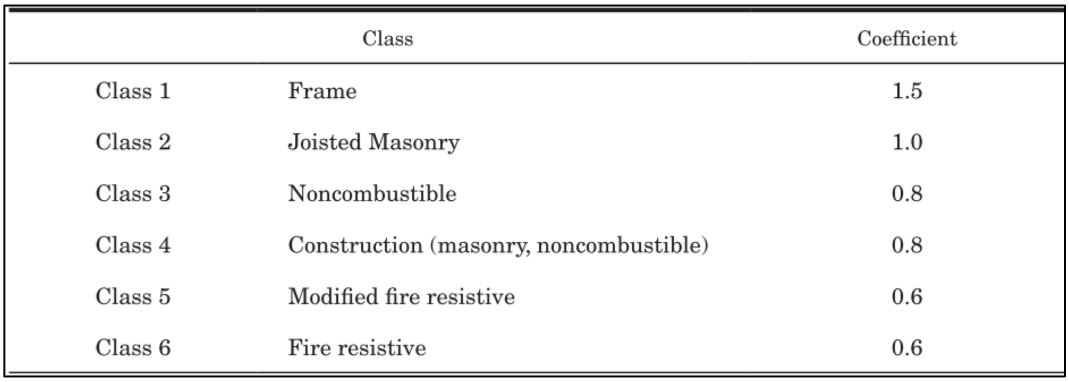
in which:

- $\boldsymbol{C_i = 18F\sqrt{A_i}}$ is a Construction coefficient,
    - $\boldsymbol{F}$ is a coefficient related to the **Class** of construction,
    - $\boldsymbol{A_i}$ $[ft^2]$ is the **Effective area** of the largest floor in the building plus 50 % of all other floors in the building

- $\boldsymbol{O_i}$ is an Occupancy factor,
- $\boldsymbol{X_i}$ is an Exposure factor and $\boldsymbol{P_i}$ is a Communication factor:

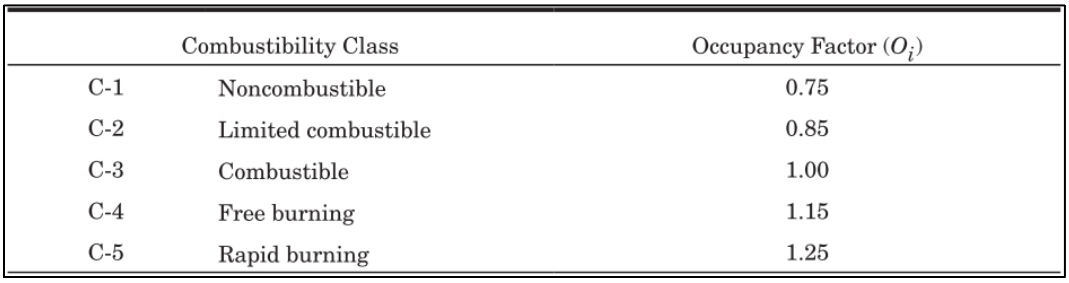
$$\boldsymbol{(X+P)_i = 1 + \sum_{i=1}^{n} (X_i + P_i) < 1.6}$$

Where **n** is the number of sides of the building.



Class		Coefficient
Class 1	Frame	1.5
Class 2	Joisted Masonry	1.0
Class 3	Noncombustible	0.8
Class 4	Construction (masonry, noncombustible)	0.8
Class 5	Modified fire resistive	0.6
Class 6	Fire resistive	0.6

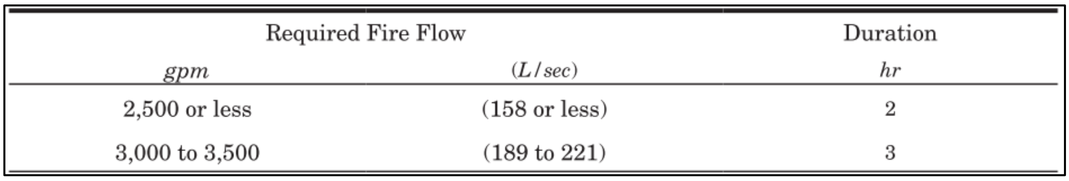
Table 2: Values of coefficient (F) construction class [2]**.**



Combustibility Class		Occupancy Factor (O_i)
C-1	Noncombustible	0.75
C-2	Limited combustible	0.85
C-3	Combustible	1.00
C-4	Free burning	1.15
C-5	Rapid burning	1.25

Table 3: Occupancy factors for selected combustibility classes [2]**.**

It is also worth reporting again below fire duration recommendation by [2].



Required Fire Flow		Duration
gpm	(*L*/*sec*)	*hr*
2,500 or less	(158 or less)	2
3,000 to 3,500	(189 to 221)	3

Table 1: Fire flow durations [2].

4.2 *Additional water evaluation*

In order to assess the **Additional Needed Water (ANW)** is firstly necessary to evaluate the maximum hydrants discharge capacity $\boldsymbol{F}\ [L/s]$, and so the base available water. Hydrants could be modelled in the network as **emitters** with a **discharge coefficient C** depending on the hydrant's diameter. Emitter flow rate varies as a function of the pressure available at the node:

$\boldsymbol{q = C\, p^{\gamma}}$, [75], where:

- $\boldsymbol{q}$ is the flow rate in $[L/\mathrm{s}]$,
- $\boldsymbol{p}$ is the pressure in $[m]$,
- $\boldsymbol{C}$ is the above-mentioned discharge coefficient in $[\frac{L}{s*m}]$ and
- $\boldsymbol{\gamma = 0.5}$ is the pressure exponent

Discharge coefficient has been evaluated by means of Flow Test Procedures by [113] and here below the relation between **C** and Diameter is shown:

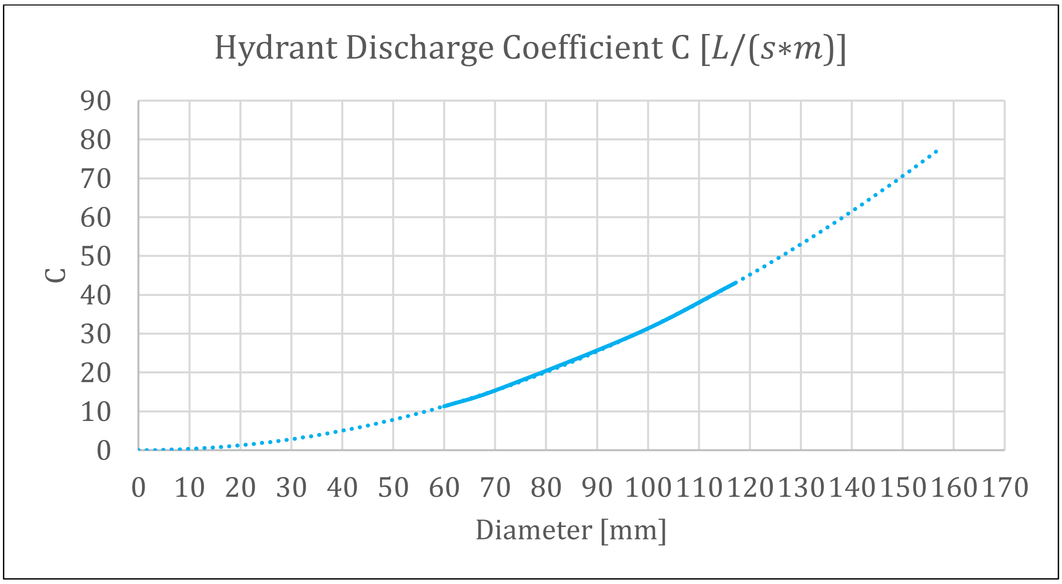


Figure 10: Hydrant Discharge Coefficient C.

Consequently, ANW will be evaluated as the difference between the Needed Water (NW) and the Available Water (AW) deriving from the maximum available hydrants' discharge capacity:

$$\boldsymbol{AW = F * d \quad [m^3]}$$

$$\boldsymbol{NW = NFF * d \quad [m^3]}$$

$$\boldsymbol{ANW = NW - AW = (NFF - F) * d \quad [m^3]}$$

Where $\boldsymbol{d}$ is the probable fire duration. Fire duration is modelled by means of an **exponential CDF**: it has as only parameter the **mean** $\boldsymbol{\mu}$ retrieved from Table 1:

$$\boldsymbol{\lambda = 2\ hours}$$

$$\boldsymbol{CDF = 1 - e^{-\lambda d}}$$

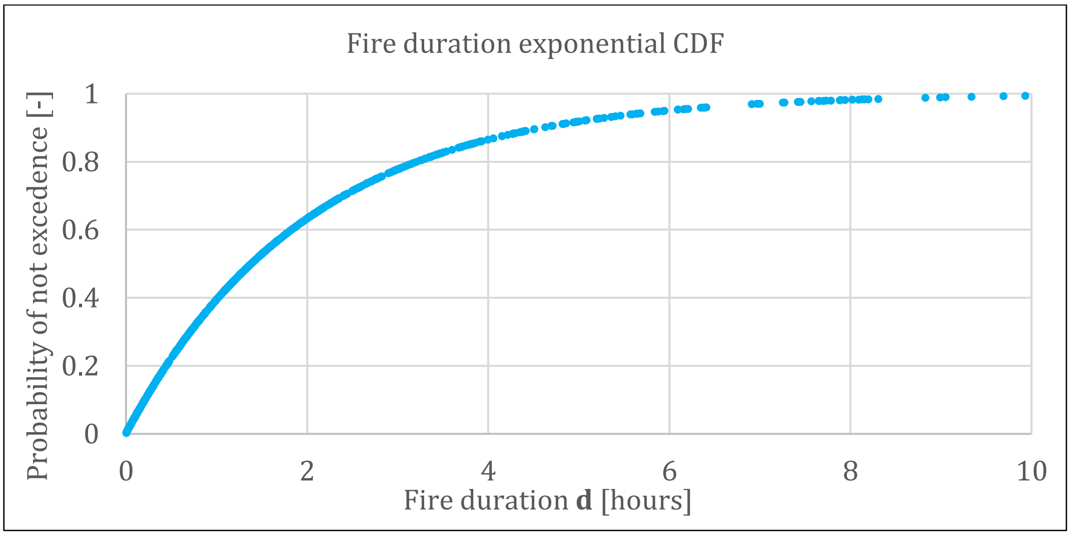


Figure 11: Fire duration exponential CDF.

DATA PRODUCING

Within European NAIADES Project [114] there is a need of producing data about critical events, like fires, that would otherwise be rare and, thus, difficult to collect experimentally: this could help in an AI system teaching, according to Project's goals. To this aim, a lot of data about probable fires are virtually generated to assess the most probable **ANW,** considering:

- Variability of **NFF** through:
    - varying building dimension through varying $\boldsymbol{A_i}$ and number of building floors,
    - varying building Class of construction $\boldsymbol{F}$
    - varying building **Occupancy factor** $\boldsymbol{O_i}$
    - varying building Exposure factor $\boldsymbol{X_i}$ and Communication factor $\boldsymbol{P_i}$
- Variability of **d** through its exponential **CDF sampling** with different **probabilities of occurrence**

All these variabilities are combined together into ANW formulation to give a database and retrieve most probable water volume to supply from it.

F is intended to be the **average maximum capacity** of the hydrants considering the **Scenario** condition (Paragraph 3.1).

Methodology applied to Case Study can be found in Paragraph 7.3.

5 CASE STUDY

In this Chapter the Case Study is presented and then, in Chapters 6 and 7 both Methodologies presented in Chapters 3 and 4 are applied to Case Study. Benalúa’s network is available within the European Project NAIADES [114], in which, one of the two Supervisors of this work, Prof. Leonardo Alfonso, is involved: it is a project to support modernization and digitization of water sector through sustainable and eco-friendly methodologies.

5.1 *Benalúa*

Benalúa is a “barrio” (neighborhood) of Alicante, located in the East of the Spain and confining with 4 others Alicante’s neighborhoods. From Alicante’s municipality website [115], has been possible to get Benalúa’s database of population through years from 1997 to 2018, so to obtain its trend, reported in Figure 12.

Population in 2017 (year for which both Methodologies have been applied) was

$$\boldsymbol{N_{us} = 9200}$$

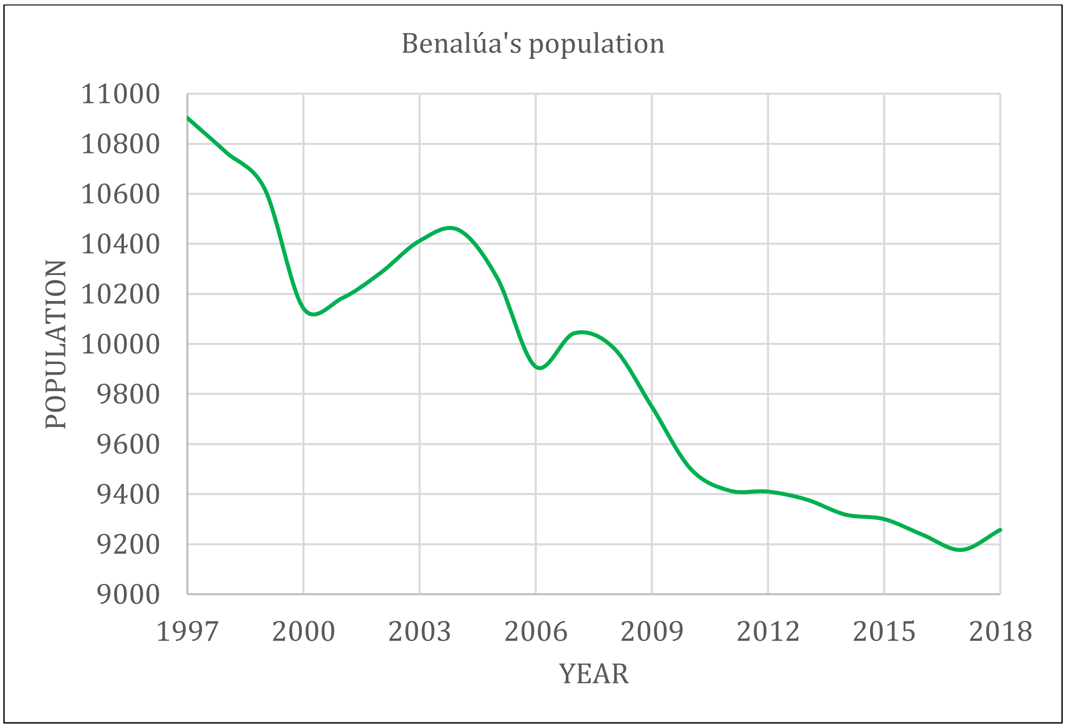


Figure 12: Benalúa’s demographic trend [115]**.**

Also, detailed data about **Water Demand** are available as well as data about the **WDN**. All info is available within a Geographical Informational System (GIS) Database. Below all these data are presented.

TOPOLOGY and OROGRAPHY

Physical connections between all WDN elements and their geographical location are known (Figure 14, Figure 13).

OROGRAPHY

All nodes' elevation is known. Benalúa's average Elevation on average water level is **16.55m.**

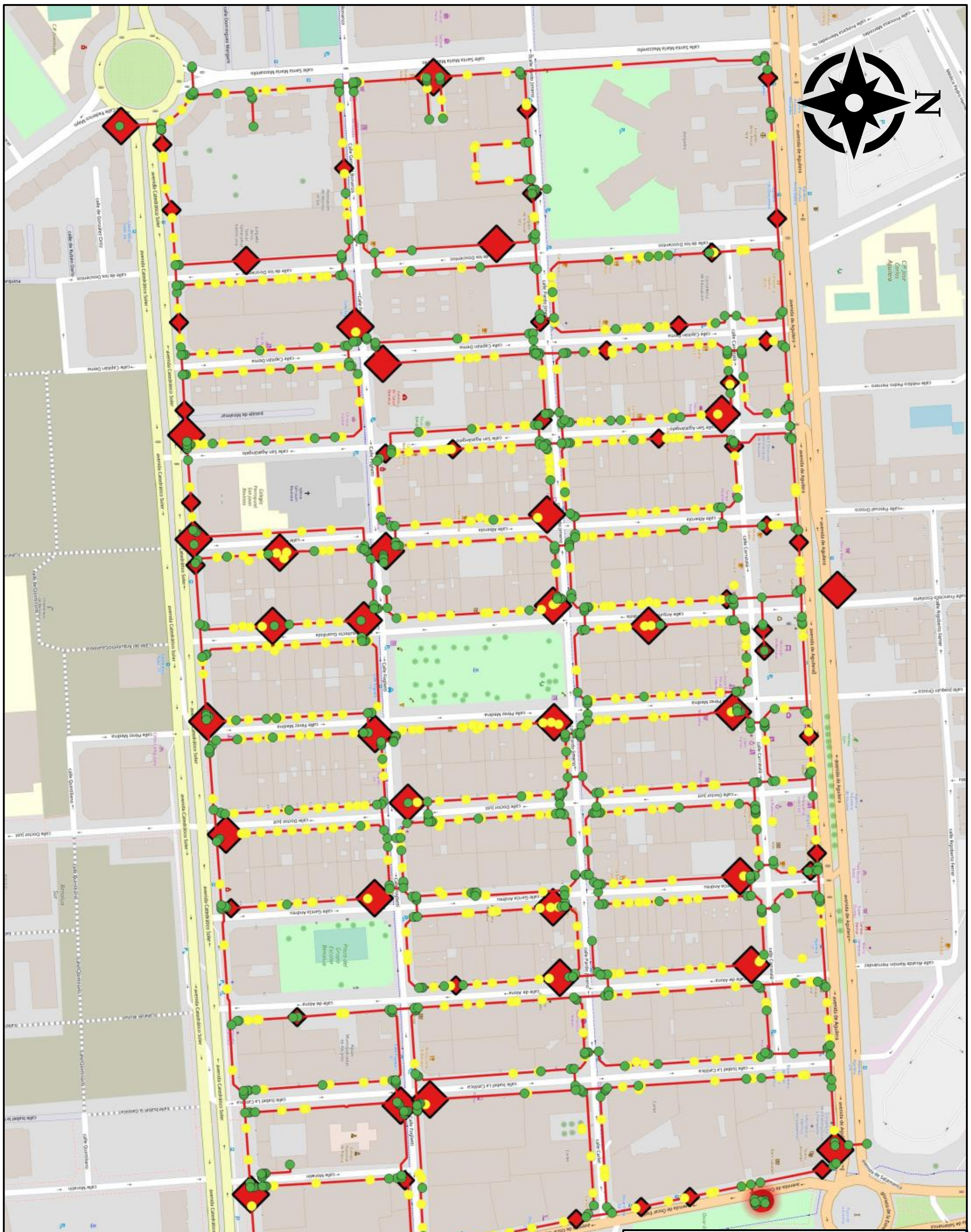


Figure 14: Benalúa's WDN topology (a).

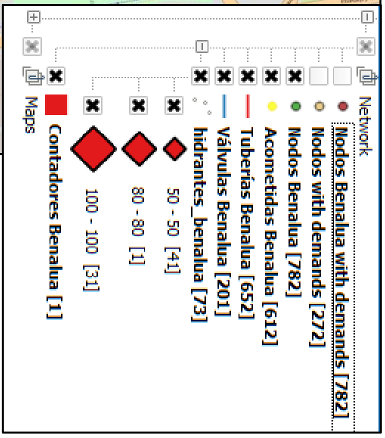


Figure 13: Benalúa's WDN Legend.

WDN COMPONENTS

Nodes are 783:

- of which 236 nodes actually deliver demand: each of them averagely supplies 30 people (here below, water demand in blue in a heat map)
- location and elevation are known
- weekly average demand is known.

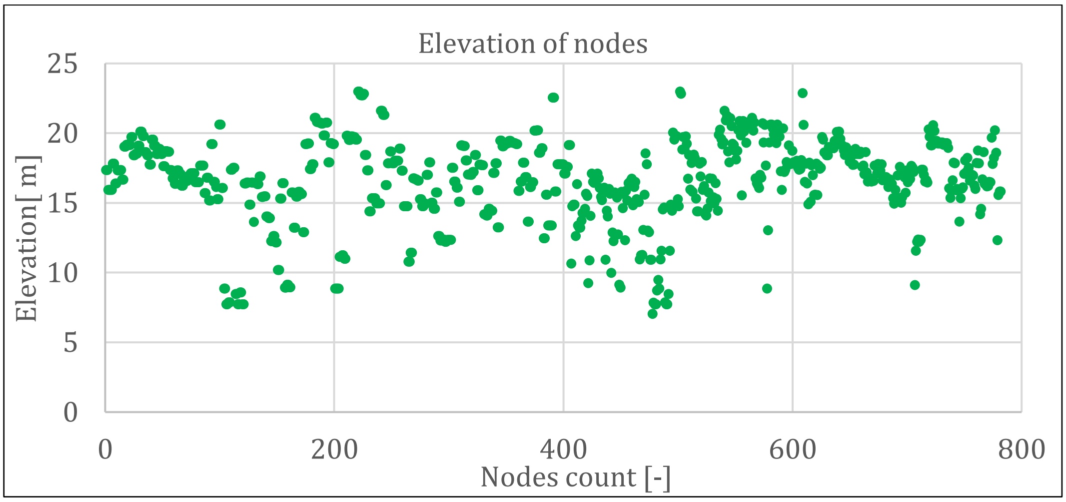


Figure 15: Nodes' elevation.

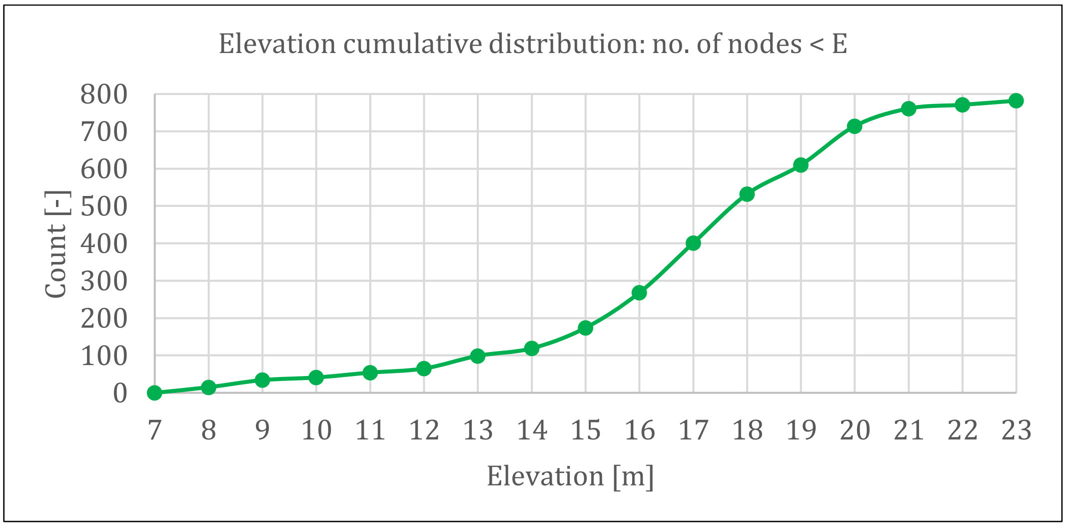


Figure 16: Nodes' elevation cumulative distribution.

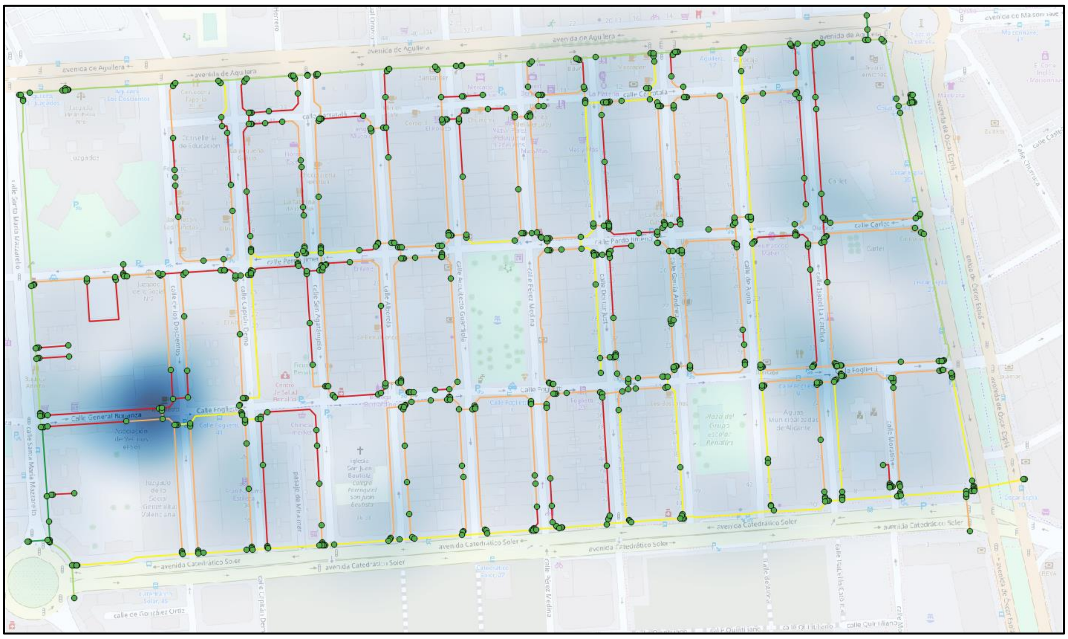


Figure 17: Water demand heat map.

Pipes are 654:

- location, length and DN are known
- CW roughness is known
- material is **not** known.

	Pipes' diameters sorting	
	Count	Diameter [mm]
	1	25
	1	40
	9	50
	10	60
	8	70
	96	80
	335	100
	130	150
	57	200
	5	250
	2	300
Total pipes	654	
Diameters used		11
Average diameter		120
Most used (Mode)		100
Smaller		25
Bigger		300

Table 4: Pipes' count.

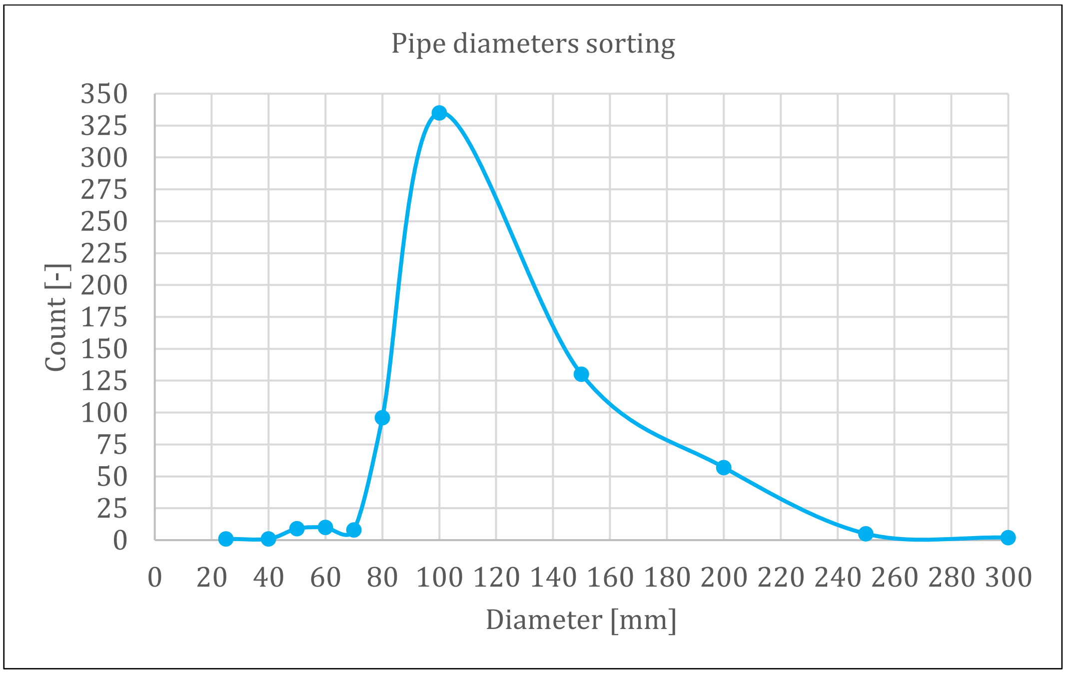


Figure 18: Pipe diameters sorting.

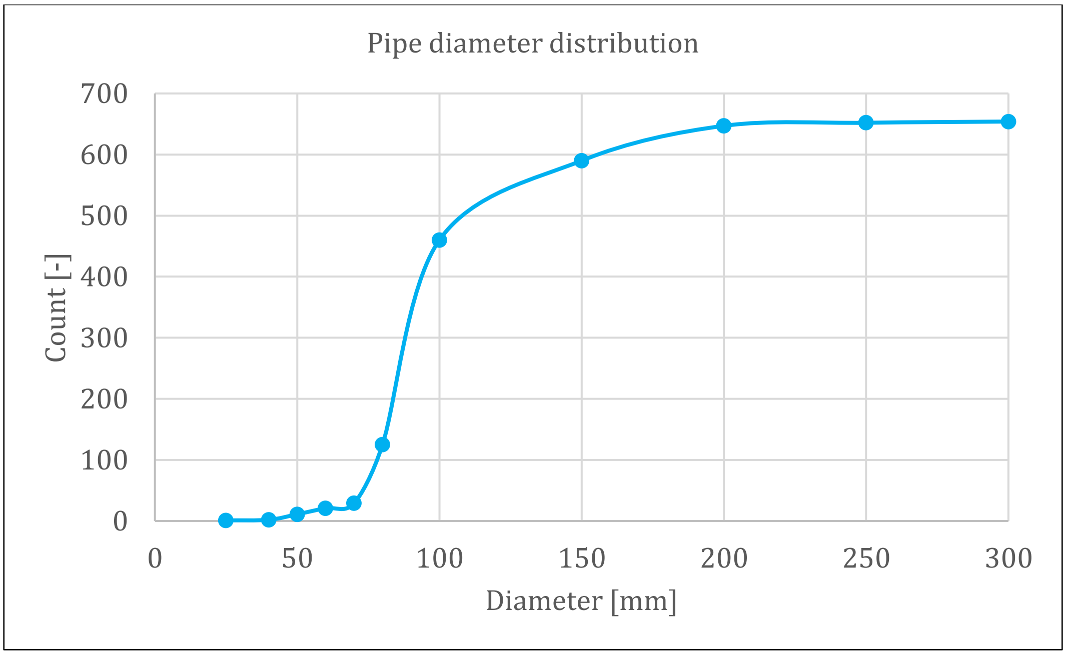


Figure 19: Pipe diameter sorting distribution.

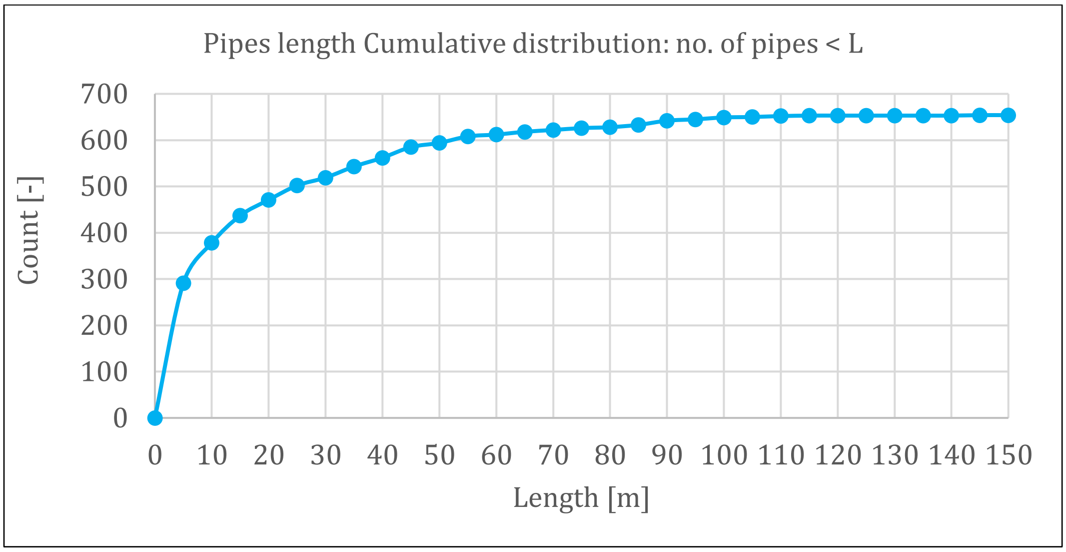


Figure 20: Pipes length Cumulative distribution.

Valves are 202:

they are all supposed to be fully open or fully closed.

Valve1 is a dummy valve: this PBV valve, located upstream the whole network, and just downstream **Tank1,** was calibrated to match pressure measurements in WDN’s **node 253** with model analysis’ pressure results (see Figure 27 for details).

Loops are 74.

Hydrants are 73 (red diamond markers in Figure 14) and they are all underground hydrants of which:

- 31 hydrants DN100
- 1 hydrant DN80
- 41 hydrants DN50.

WATER DEMAND

Water demand data are available through data collecting with a Flow Meter “Contador” placed upstream the WDN and by water accounting at delivery points. **7 days of hourly measurements** (resolution=1hour) **at Contador were conducted in July 2017.** Briefly an **average day trend** is reported below.

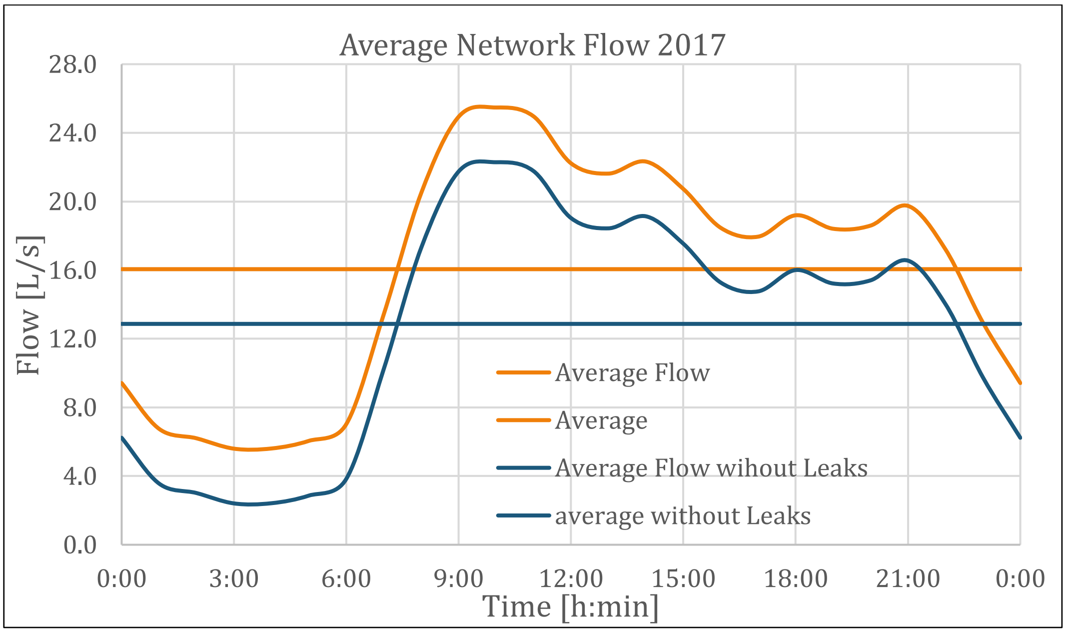


Figure 21:Average day in July 2017.

Total consumption m^3/week Summer 2017	9'712.03
Actual consumption m^3/week 2017	7'783.05
Pérdidas 2017	1'928.98
Connections count [-]	612
Inhabitants 2017	9177
DOTAZIONE IDRICA 2017 [L/ab day]	151

It is worth remembering that **Figure 21** shows the **total network entering the WDN** through the **WDN main pipe** called **Contador.**

According to what explained in Paragraph 3.1 about **Leakages,** an additional **+22%** of demand has been taken into account (accordingly with **water accounted at delivery points)** to consider the leakages in the network and, then, execute a correct network analysis. Here on the left are reported data about total water **delivered** and **accounted** in 2017.

Ratio between Total & Actual Consumptions
1.247844319

Rendimiento
80.14%

Here below are reported some data about water demand **accounted** at nodes.

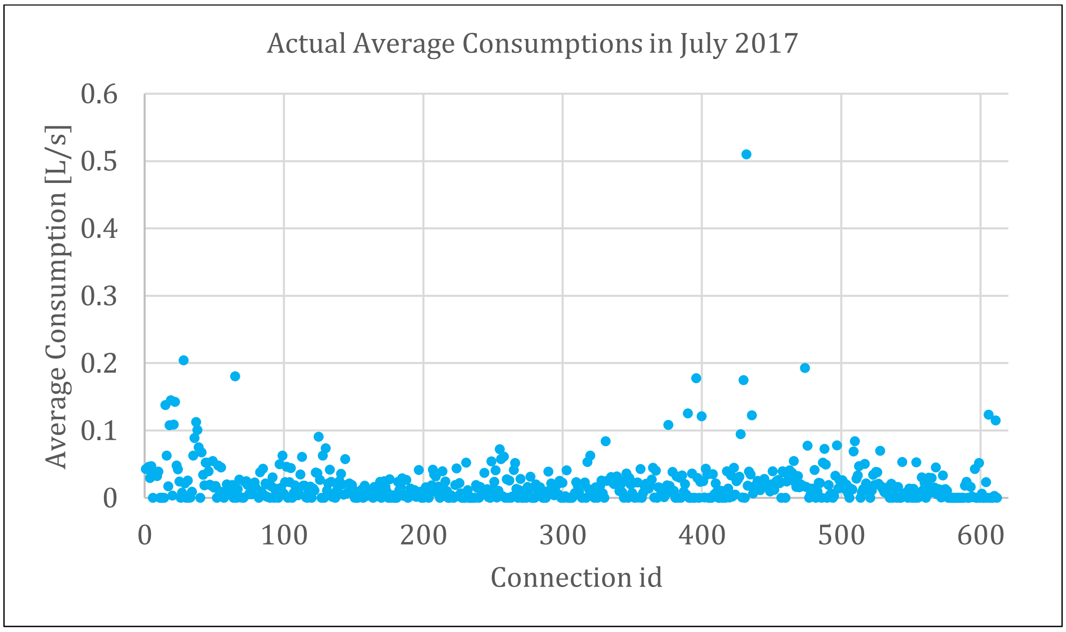


Figure 22: accounted water demand in July 2017.

Definitely, in the network , considering +22% Leakages, the **average flow** is:

$$\boldsymbol{Q_m = 16\ L/s}$$

The **maximum observed flow** was:

$$\boldsymbol{Q_{observed} = 25.5\ L/s}$$

In accordance to what has been said about **water peak demand modelling,** the **Peak Coefficient** Gumbel CDF is reported below.

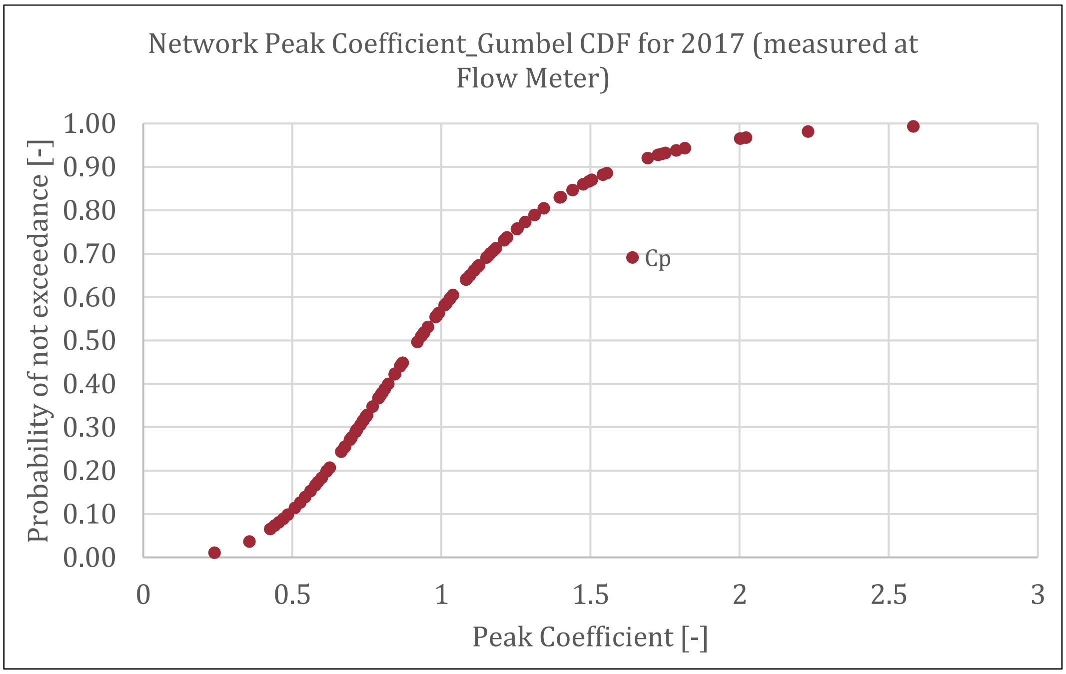


Figure 23: Network Peak Coefficient Gumbel CDF.

In addition, since a **critical Peak Demand** with a **probability of not exceedance**

$$\boldsymbol{P[S] = 99\%}$$

was chosen, corresponding **Peak Coefficient** is:

$$\boldsymbol{C_P = 2.5}$$

and **Peak Demand** in the network is, consequently:

$$\boldsymbol{Q_P = 40\ L/s}$$

This flow corresponds to **Scenario** condition (see Paragraph 3.1).

PRESSURE MEASUREMENTS

Pressure measurements are also available for Benalúa’s WDN. They were taken at **Node 253 at the same** time that **network flow** was recorded at Contador. Here below is reported Node 253 location.

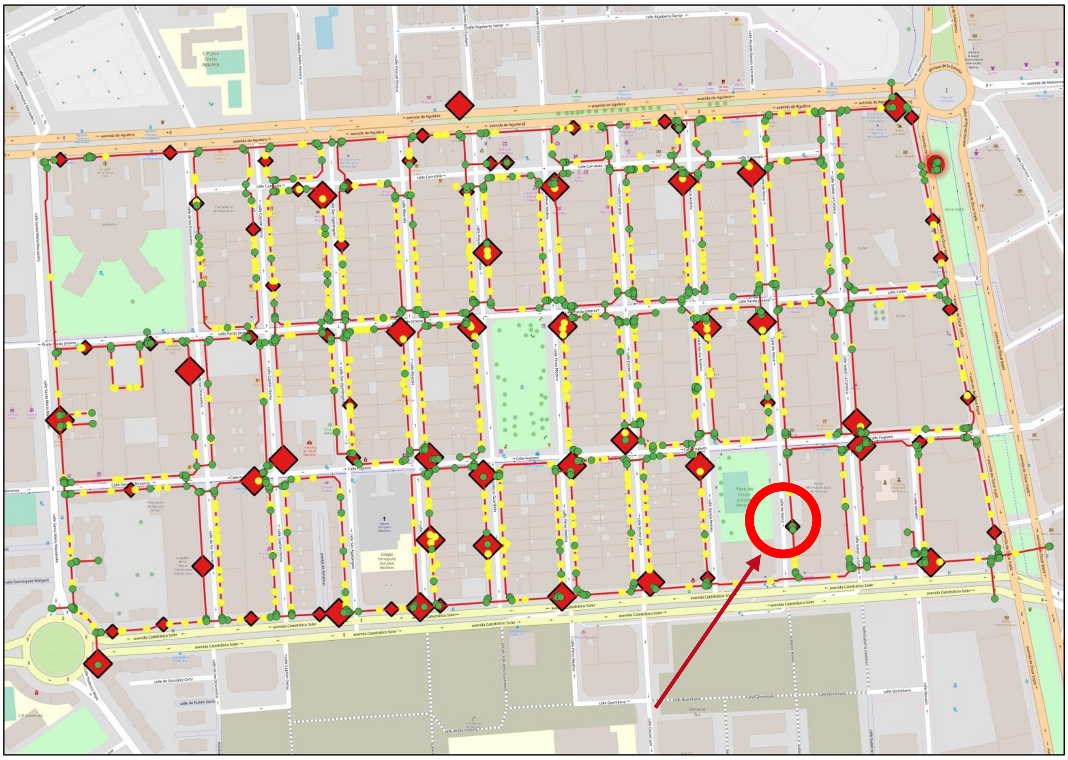


Figure 24: Node 253 location: pressure measurements were taken here.

It is also where local water company is located.

Since **measurements** were taken for **7 days** in **July 2017**, an **average day is shown,** similarly to what has been done for network flow.

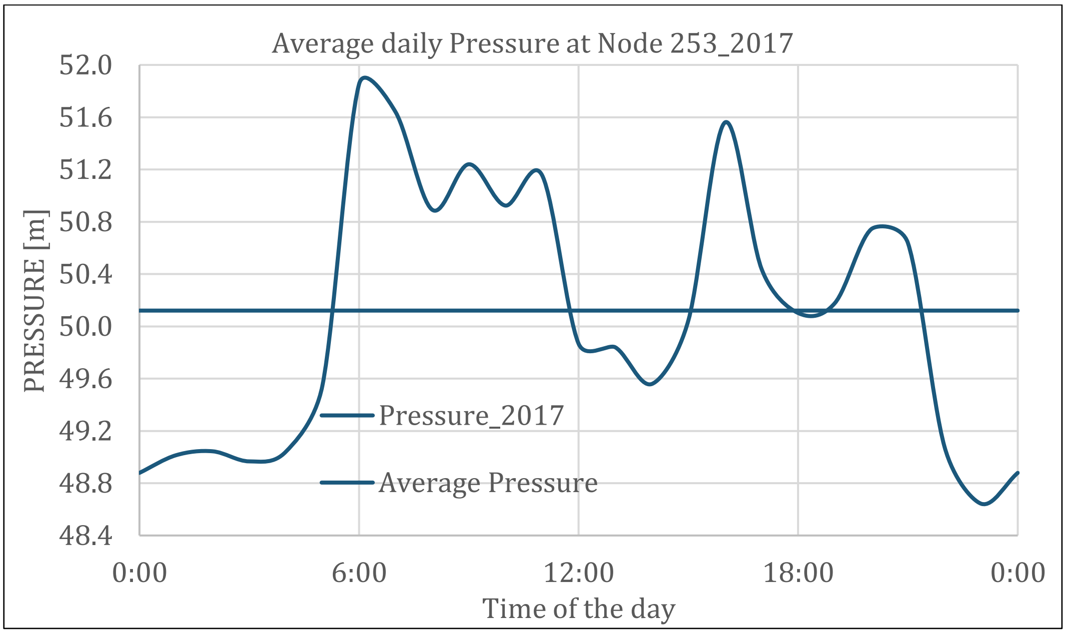


Figure 25: Average daily Pressure at Node 253 in July 2017.

Note: it is reasonable to think that this Case Study's WDN is a District Metered Area (DMA). Usually DMAs allow improving pressure management, water budget and leaks detection, compared to classical redundantly looped networks [116].

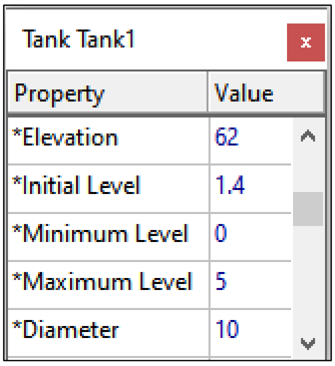
CALIBRATING

Calibrating the network was needed for two reasons:

1. **No info** about the kind of water source is available for Benalúa's WDN: it is known **where** water enters the Benalúa's DMA (Contador, see Figure 14) but it is **not known how** water is stored or supplied to DMA.
2. **Pressure results from network analysis (Epanet** [75]**) did not match with pressure measurements on field at Node 253**

These issues were tackled in the way explained below.

1. **Tank1** has been modelled, so that **maximum pressure variability observed in average day** (almost $\Delta P = 3.2m$,see Figure 25) **matches** with **maximum water level variability Δw in Tank1**, in an average conditions simulation.



Property	Value
*Elevation	62
*Initial Level	1.4
*Minimum Level	0
*Maximum Level	5
*Diameter	10

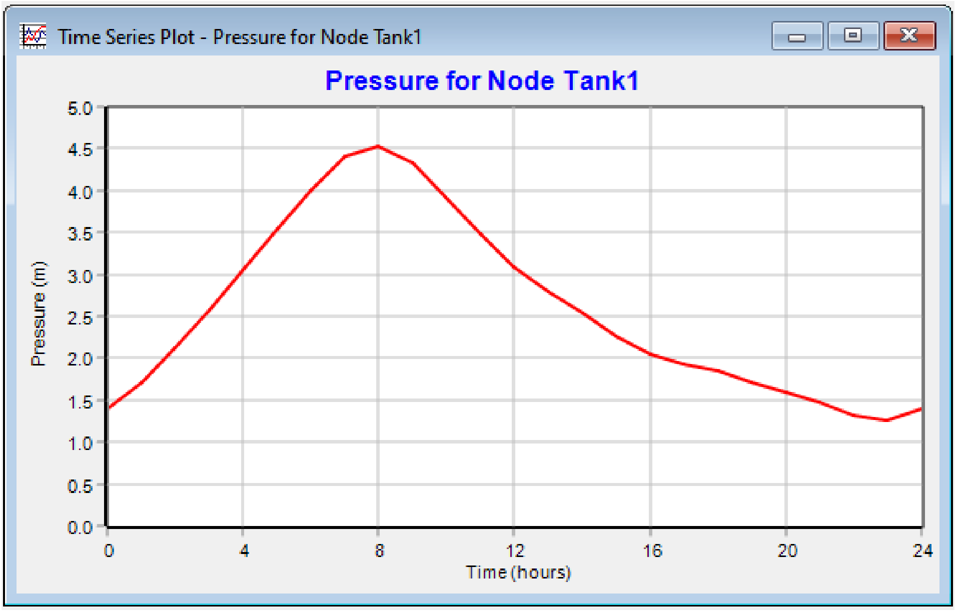


Figure 26: Tank1 calibrating.

Tank1 is placed, of course, upstream the WDN and **it is supplied with**

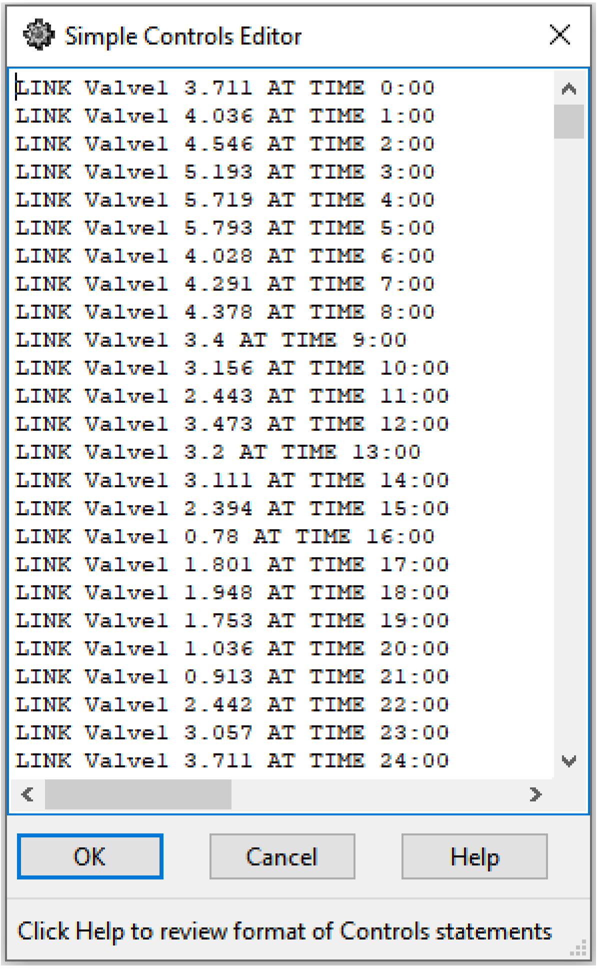
$$Q_m = 16\ L/s$$

2. For roughly calibrating the network towards **network analysis pressure results** at Node 253 that initially differed from **pressure measurement** at the same Node, it was necessary to **rule a dummy Valve1 so that Pressure Results and Pressure Measurements matched.** Practically,

hourly head losses were imposed manually (the trial and error old way), until pressure measurements and pressure results from analysis matched.

Note: Point 1 and Point 2 were manually iteratively calibrated at same time until a good correspondence between pressures was found.

Valve1 is placed downstream **Tank1**.



```
LINK Valve1 3.711 AT TIME 0:00
LINK Valve1 4.036 AT TIME 1:00
LINK Valve1 4.546 AT TIME 2:00
LINK Valve1 5.193 AT TIME 3:00
LINK Valve1 5.719 AT TIME 4:00
LINK Valve1 5.793 AT TIME 5:00
LINK Valve1 4.028 AT TIME 6:00
LINK Valve1 4.291 AT TIME 7:00
LINK Valve1 4.378 AT TIME 8:00
LINK Valve1 3.4 AT TIME 9:00
LINK Valve1 3.156 AT TIME 10:00
LINK Valve1 2.443 AT TIME 11:00
LINK Valve1 3.473 AT TIME 12:00
LINK Valve1 3.2 AT TIME 13:00
LINK Valve1 3.111 AT TIME 14:00
LINK Valve1 2.394 AT TIME 15:00
LINK Valve1 0.78 AT TIME 16:00
LINK Valve1 1.801 AT TIME 17:00
LINK Valve1 1.948 AT TIME 18:00
LINK Valve1 1.753 AT TIME 19:00
LINK Valve1 1.036 AT TIME 20:00
LINK Valve1 0.913 AT TIME 21:00
LINK Valve1 2.442 AT TIME 22:00
LINK Valve1 3.057 AT TIME 23:00
LINK Valve1 3.711 AT TIME 24:00
```

Click Help to review format of Controls statements

Figure 27: dummy PBV Valve 1 configuration.

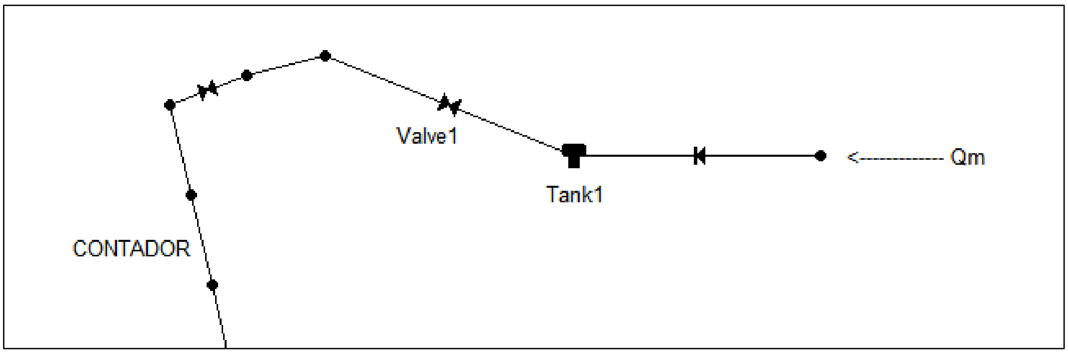


Figure 28: Tank1 and Valve1 were adapted to calibrate WDN.

6 SOFTWARE IMPLEMENTATION AND FRAMEWORK

In this Chapter the Methodology for Rehabilitation is implemented in software. With no doubt, technical progresses in computational resources have led to new developments in WDNs related researches [117], so why do not take advantage of them?

So far, Methodology about Rehabilitation has been presented in Chapter 3: the aim is to tackle a MOOP in which, optimally upgrading one or more pipes leads to economically sustainable network rehabilitation towards deficient hydrants, that, in case of a critical fire in any point of the city, within a critical situation too (Scenario), may miss minimum firefighting requirements and cause reliability issues and additional risks.

Also, Case Study has been presented in Chapter 5: MOOP is applied to it through combining different software and finally Results will be presented and discussed in Chapter 7, along with Results from Methodology for Operation presented in Chapter 4.

It is worth remembering that network analysis simulations depend on:

- Location of fire event: which one, among the 73 hydrants, is operated,
- Duration of fire event: a 2 hours event is used for EPSs,
- Level in Tank1 when takes place: his is why using EPS is necessary,
- User demand when fire takes place: deterministic Peak Demand with $\boldsymbol{C_P = 2.5}$ is considered

All these conditions make the **Scenario** explained in Paragraph 3.1.

6.1 GIS database

QGIS 2.18.21 has been used for the purpose. The following shape files are available:

- ✓ “Acometidas Benalua.shp”
- ✓ “Contadores Benalua.shp”
- ✓ “Nodos Benalua.shp”
- ✓ “Tuberías Benalua.shp”
- ✓ “Válvulas Benalua.shp”
- ✓ “hidrantes_benalua.shp”

Figure 13 and Figure 14 represent the WDN. “Acometidas” are the actual **average accounted demands**, but they have been merged and assigned to the **nearest node** of “Nodos”, with **“Nearest Hub” QGIS tool**, since no water demands distributed along pipes are modelled in this work (Paragraph 3.1).

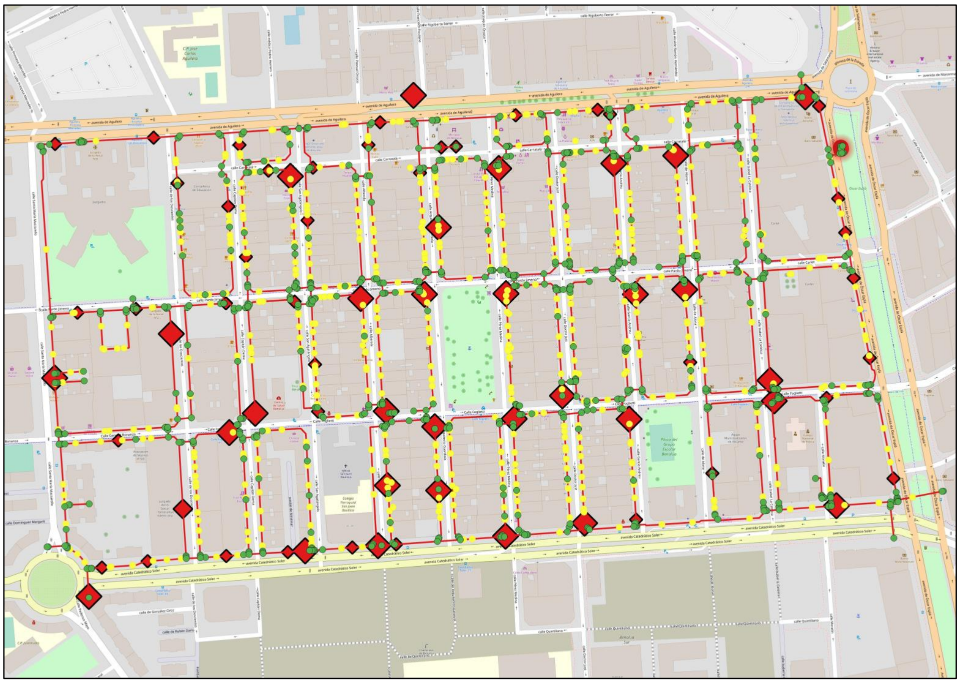


Figure 29: Benalúa’s WDN topology (b).

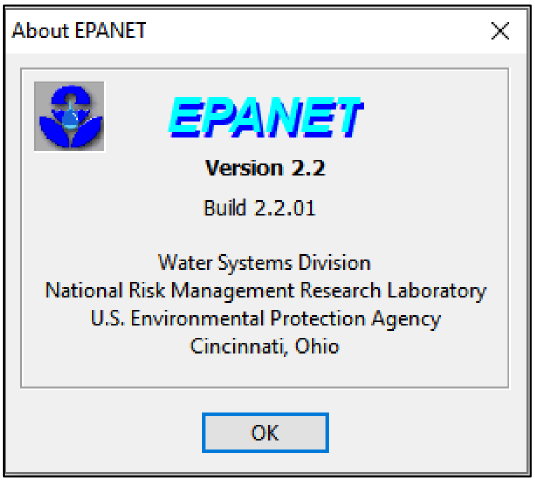
Hydrants too have been assigned to the **nearest respective node** with the same tool.

Once all shape files have been arranged and demands have been attributed to nodes, the next step is to export the WDN in EPANET hydraulic simulator [75]. Many QGIS Tools are available for this purpose, but in this specific case, **manually writing** a **.inp** file in a common text editor like Notepad has been found to be the most effective and precise way.

6.2 *EPANET 2.2 (PDA)*

The **.inp** Epanet input file has been manually set up, taking care of the fact that, since EPANET 2.2 with PDA is being used, some additional parameters have to be carried out.

EPANET 2.2 is an **open source**, **unofficial version** and a **beta release** of the famous EPANET 2.0 by USEPA [75]. The release used is the **build 2.2.01.** Author thanks **USEPA** and **OpenWaterAnalytics** for making possible to use this Epanet version with a graphical UI [118].


About EPANET

EPANET

Version 2.2

Build 2.2.01

Water Systems Division
National Risk Management Research Laboratory
U.S. Environmental Protection Agency
Cincinnati, Ohio

Figure 30: EPANET 2.2.01 with PDA.

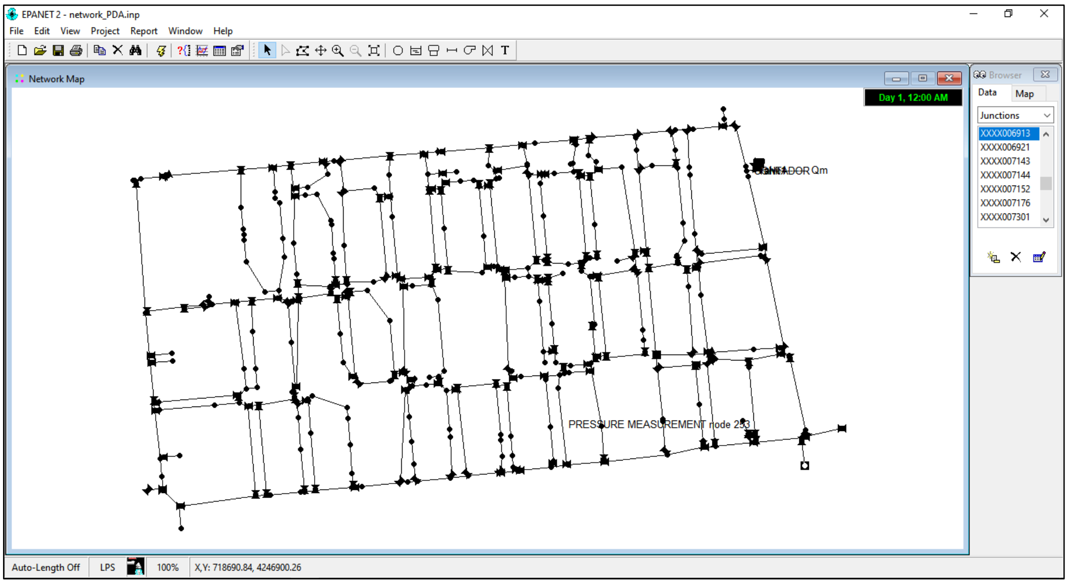
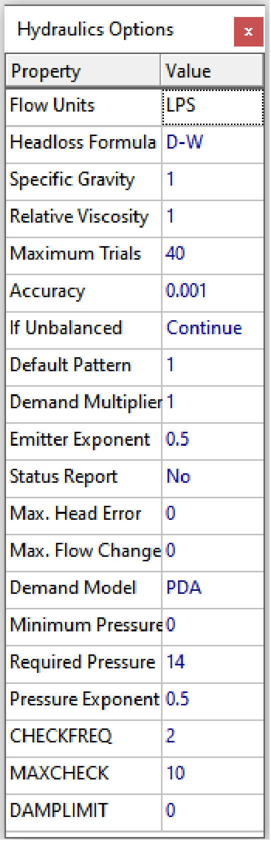


Figure 31: Benalúa's WDN in EPANET 2.2.01.

The most useful tool that EPANET 2.2 brings with it, is PDA. The user can switch between classical DDA or new PDA that is very innovative and more physically correct for the reasons presented in Paragraph 2.3.

PDA parameters need to be set up in addition to the classical DDA:

- **Minimum pressure**: pressure can't go below the terrain level **=0m.**
- **Required Pressure**: for hydrants, the minimum requirement is **14m** (see Paragraph 2.1.2): below this value, **full demand can't be supplied and POR has to be considered** to evaluate actual **outflow**
- **Pressure exponent**: $\boldsymbol{\gamma = 0.5}$ (see Paragraph 4.2)


Hydraulics Options

Property	Value
Flow Units	LPS
Headloss Formula	D-W
Specific Gravity	1
Relative Viscosity	1
Maximum Trials	40
Accuracy	0.001
If Unbalanced	Continue
Default Pattern	1
Demand Multiplier	1
Emitter Exponent	0.5
Status Report	No
Max. Head Error	0
Max. Flow Change	0
Demand Model	PDA
Minimum Pressure	0
Required Pressure	14
Pressure Exponent	0.5
CHECKFREQ	2
MAXCHECK	10
DAMPLIMIT	0

Figure 32: Hydraulic Options

NOTES ON NETWORK ELEMENTS

About nodes: some nodes have only demand, some nodes only have a hydrant, some other nodes may have both demand and hydrant.

About pipes: pipes material is not known, but **CW roughness is = 0,6** for almost all pipes.

About valves: they actually don’t take role in any of the Methodologies and they are considered to be all **fully open** apart for **dummy Valve1.**

About hydrants: they are assigned to nodes as additional **demands.**

6.3 *Python 3 scripting and implementation*

Even though the graphical EPANET UI is very useful for some aims, it only allows to run **one manual EPS at a time**. Since MOOP requires many runs to analyze different network configurations (see Paragraph 3.2.4 in which Greedy Algorithm is presented), some automation is required to shorten time spent in analysis. To this aim the **Epanet 2.2 Programmer Toolkit** [119] and an **Epanet Toolkit Python Wrapper by OpenWaterAnlytics** [120] have been both used and combined into Python 3 scripting.

Python 3 is a high-level programming language. It has been used for its user-friendliness. Specifically, an implementation of Python 3.7.4 [121] has been used with the Spyder 4 code editor within a 32bit Anaconda environment [122]. A 32bit version has been used because the **Epanet 2.2 Toolkit library (“epanet2.dll”)** has not been coded in 64bit architecture yet.

“epanet2.dll” is the Epanet 2.2 Toolkit **.dll** library (coded in C language, 32bit) containing the Toolkit’s functions to be called: a **wrapper** it’s a **script** that allows to call Epanet Toolkit functions in Python environment through **“epamodule.py”**.

Full code that author wrote for the specific purpose of implementing and solving the MOOP explained in this thesis work, can be found in **Appendix 1**.

Briefly, code consists in:

- Modules importing

  Apart from the built-in functions, since Python is an open source programming language, it has tons of libraries called “modules”.

- Input files and Parameters:

  Input files are retrieved, parameters of the simulation are set.

  a. Epanet network input file **.inp**
  b. Info about hydrants: as many MOOPs as hydrants are run
  c. Info about Decisional Space: pipes to be changed (see Paragraph 3.2.3)
  d. Info about **Scenario**
  e. GUMBEL Cumulative Distribution Function section
  f. Cost Function input
  g. Reading files section

- Start of Simulation

  Some operations on matrix are executed before the very simulation starts and then, here we go!

  a. Initializing pipes matrix for loops

  b. Objective Functions definitions and Output definition
  c. Epanet 2.2 Toolkit functions to set **Scenario** through the wrapper
  d. Epanet hydraulic solver initializing
  e. Algorithm starting

- Greedy Algorithm

  for and **while loops** and also **if statements** were very useful for effectively and clearly implementing MOO:

  a. Epanet runs
  b. Algorithm running and **ObFs** evaluation

- Output section

  Here MOOP's Pareto Sets of solution, and eventually other useful outputs, are exported into matrixed and then to Excel to more practically analyze the Results from simulations.

- Time elapsed

  This is an additional section in which a useful evaluation on time that simulation required takes place.

7 RESULTS AND DISCUSSION

In this Chapter, results and discussion about both issues presented in Chapters 3 & 4 are presented in two respective Paragraphs. Also, future developments about dealt topics and Methodologies are hypothesized.

7.1 Rehabilitation

To be able to compare Rehabilitation approach with MOO results it is useful to show the initial conditions in which Benalúa's WDN worked.

Firstly, **average normal conditions** are shown. Average condition means:

- **Average network demand $\boldsymbol{Q_m = 16\ L/s}$**
- **Average user demand** (as in **Figure 22**)
- **Average Tank1 water level = 1.4m**
- **no fire occurs**

Following data are obtained from **Steady State network analysis (**because of the definition of "average" itself).

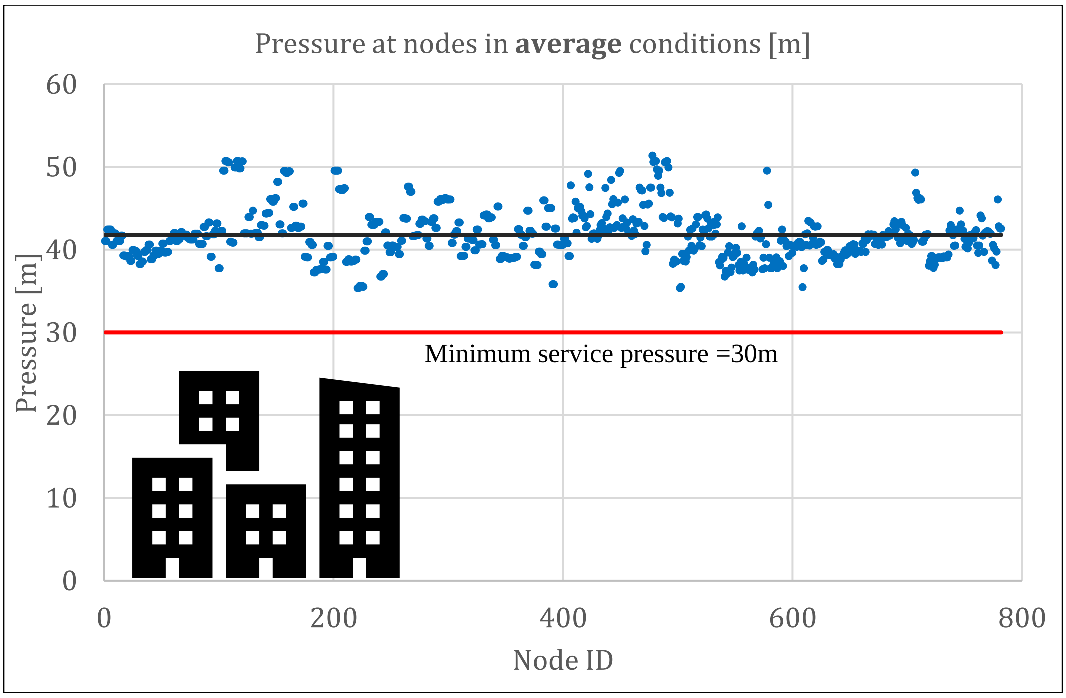


Figure 33: Pressure at nodes in average conditions.

Average pressure in **normal conditions** is **41.78m.** See also **Figure 35**.

Then, **Scenario conditions** are shown:

- **Peak network demand $Q_m = 40\ L/s$**
- **Peak user demand**
- **Minimum Tank1 water level = 0.1m**
- **no fire occurs**

Following data too are obtained from **Steady State network analysis (**deterministic Peak condition).

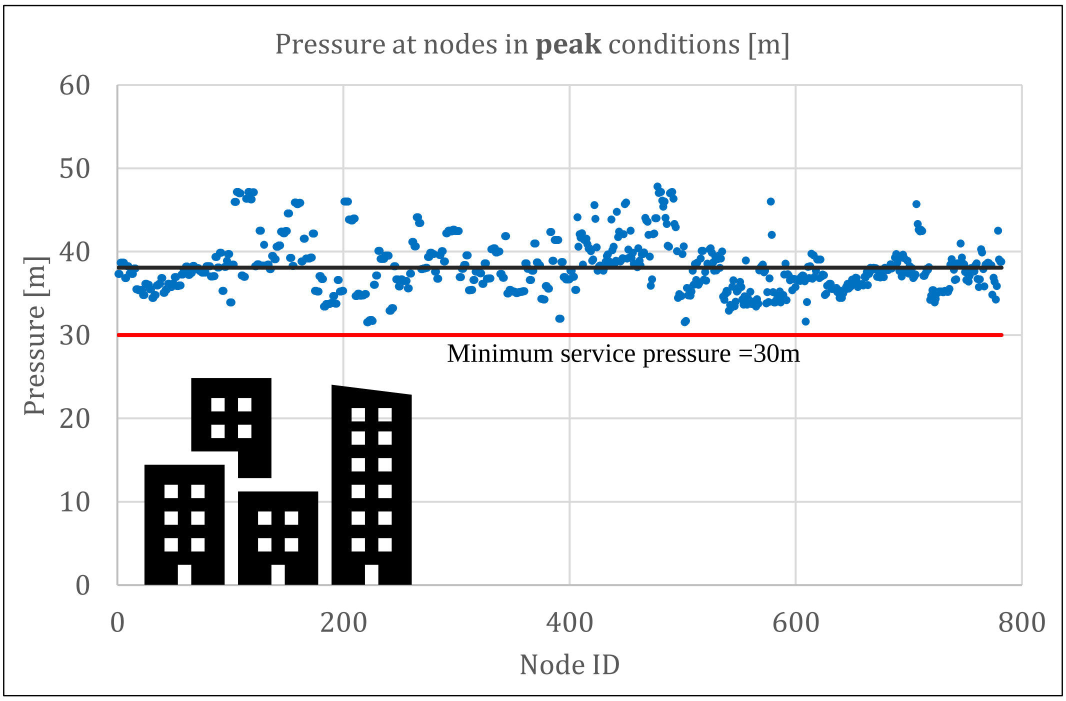


Figure 34: Pressure at nodes in peak conditions.

Average pressure in **peak conditions** is **38.08m.** See also **Figure 36.**

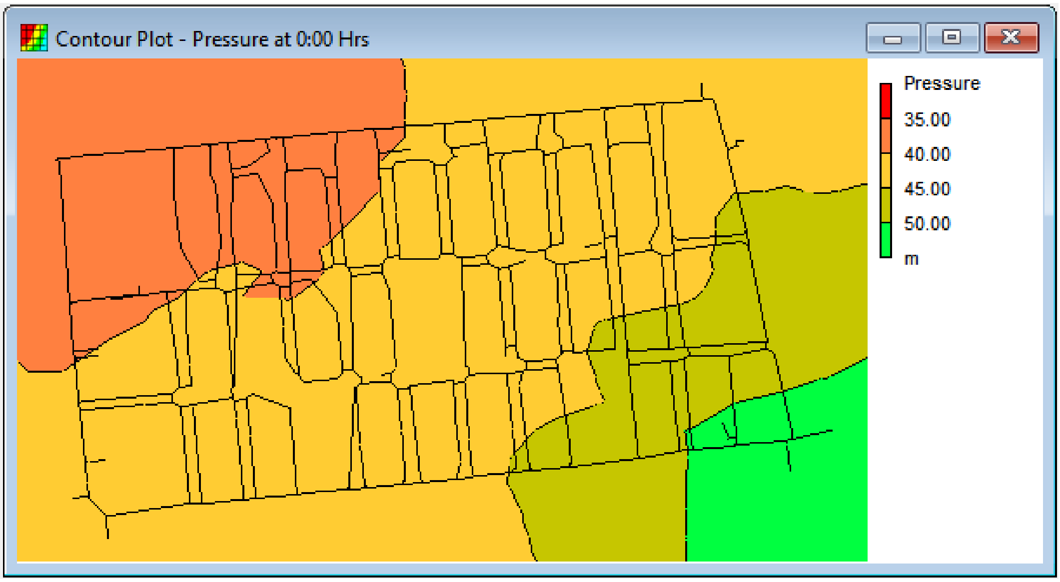


Figure 35: Network pressures in average conditions.

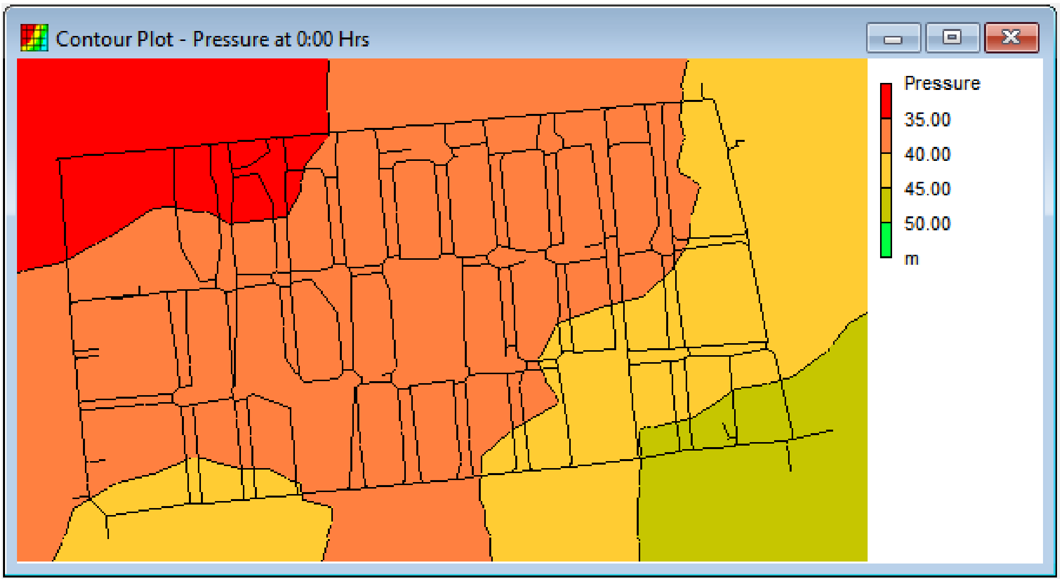


Figure 36: Network pressures in Scenario conditions.

Now, within **Scenario conditions, hydrants are (one at a time) operated, in 73 different simulations** and pressures in the network and at hydrants' nodes are checked:

- **Peak network demand $Q_m = 40\ L/s$**
- **Peak user demand**
- **Minimum Tank1 water level = 0.1m**
- **A 2 hours fire occurs with varying location one at a time**
- **$Flow = 32L/s$ is required at hydrants with**
- **A requirement of $14m$ of minimum pressure**

Following data too are obtained from **EPS network analysis.**

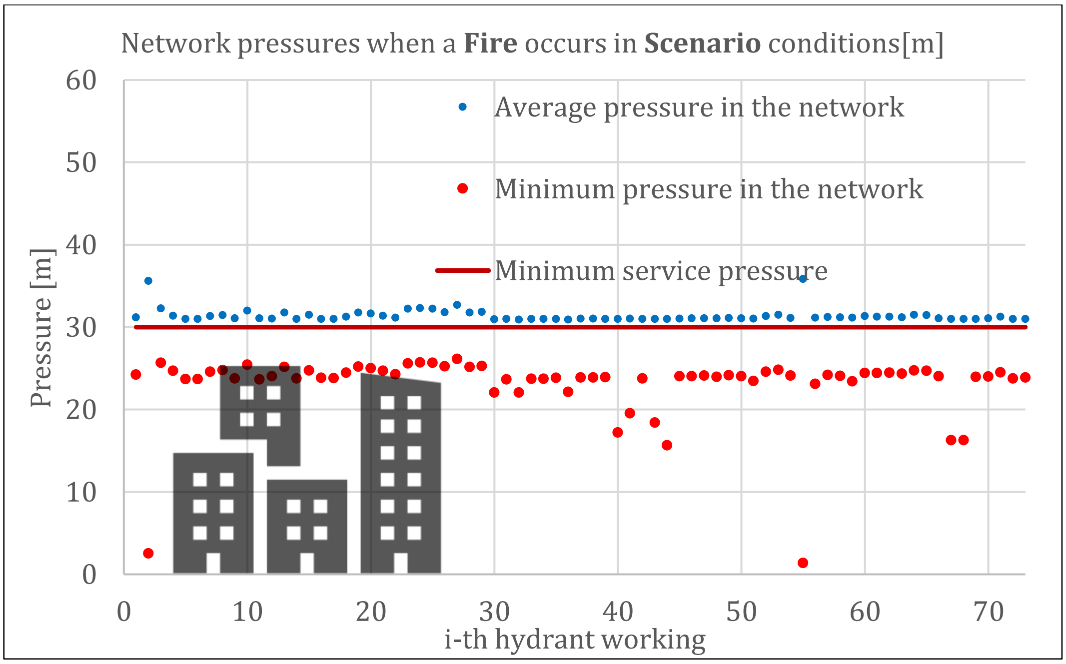


Figure 37: Network pressures when a Fire occurs in Scenario conditions[m].

When **fire** occurs in any point of the network, **average** network pressures still stay **above the minimum service pressure; minimum** network pressure don't.

Now **Residual Pressures** and **available Fire Flow at hydrant are shown.**

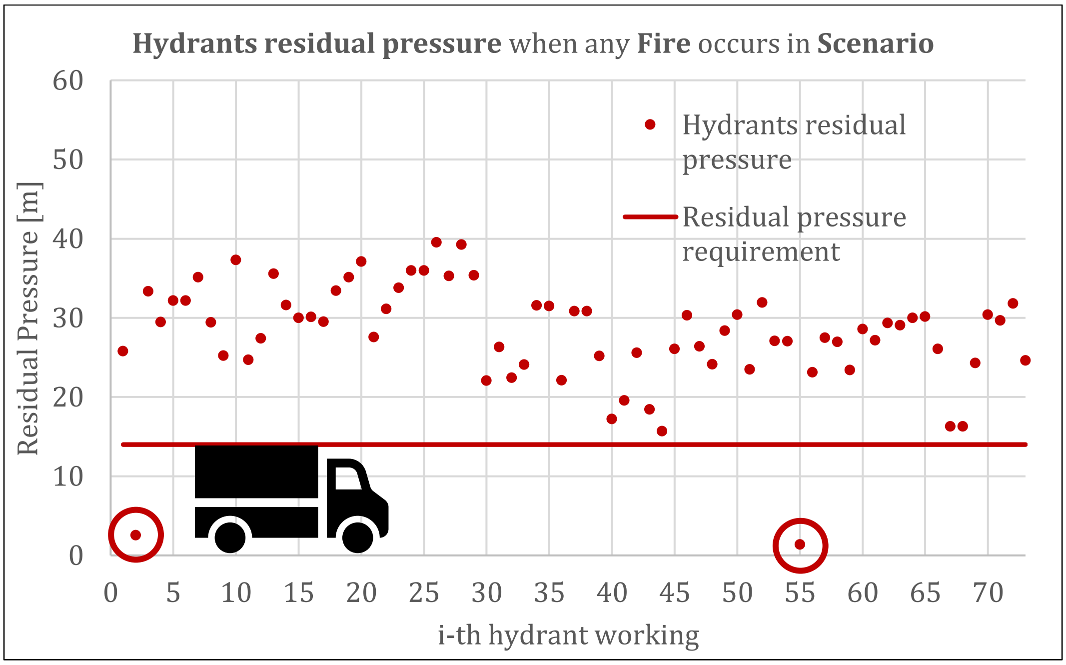


Figure 38: Hydrants residual pressure when Fire occurs in Scenario [m].

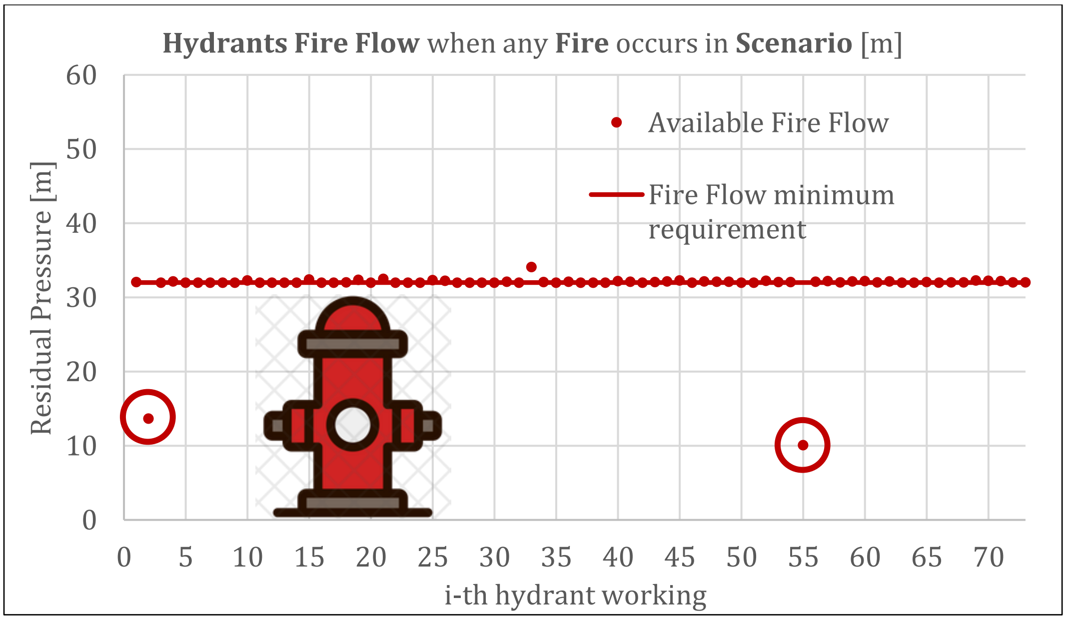


Figure 39: Hydrants Fire Flow when any Fire occurs in Scenario [m].

It can be seen that **Hydrant 2** and **Hydrant 55 don’t meet minimum requirements** and other hydrants barely do that, like 40, 41, 43, 44, 67, 68.

It can be also seen, as anticipated in Paragraph 3.2.1, how reading results in terms of **available Fire Flow** is limiting because it is imposed as a fixed **nodal demand**. Instead, reading results in terms of **Residual Pressure,** even if it is not the main aim (the main aim is to guarantee **minimum Fire Flow = 32 L/s),** allows to see results better, since more difference can be observed between different hydrants.

MOO REHABILITATION PROBLEM RESULTS

Once Problem has been introduced, stated, implemented and run, results are available, and they are here below shown.

Pareto Fronts of solutions

Pareto fronts show **near-optimal solutions** from **MOO run for each hydrant of the network separately, until constraints are violated.**

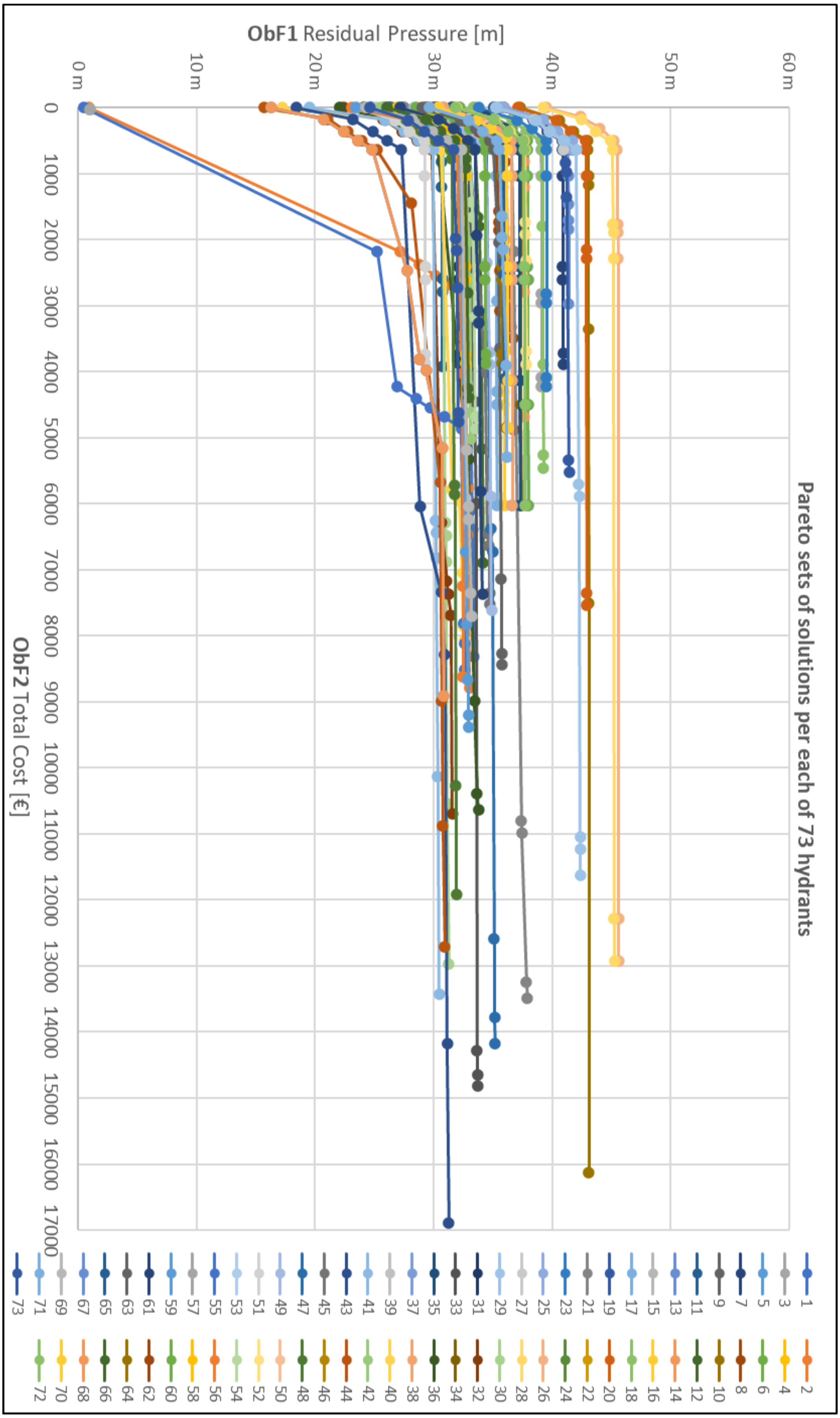
Each Pareto front represents the **optimal set of solutions** in terms of **decisional variables, by:**

- **Maximizing** $\boldsymbol{ObF1_i = Residual\ Pressure_i}$
- **Minimizing** $\boldsymbol{ObF2_i = Total\ Cost_i = \sum_{j=1}^{k} Cost_j}$
- **Optimally replacing pipes by maximizing** $\boldsymbol{ObF0_i = \left(\frac{RPI_j}{Cost_j}\right)_i}$

for the **i-th hydrant** of the network, that implicitly means, in **i different possible locations in which a fire can take place within WDN urban area.**

Here below (Figure 40), Pareto fronts are reported. See **Paragraph 3.2: Problem setting**, for additional details.

Figure 40: Pareto sets of solutions per each of 73 hydrants.


Pareto sets of solutions per each of 73 hydrants
ObF1 Residual Pressure [m]
0 m
10 m
20 m
30 m
40 m
50 m
60 m
ObF2 Total Cost [€]
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59 61 63 65 67 69 71 73
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72

With different colours are represented 73 WDN hydrants: for each of them a MOOP has been run and a Pareto set of solutions has been obtained.

Some observations may be done:

1. Hydrant 2 and Hydrant 55 are missing minimum requirements in **Scenario conditions** when **ObF2=0€,** that is no rehabilitation is provided (original condition),
2. Hydrants 40, 41, 43, 44, 67, 68 initially meet minimum requirement but are below 20m pressure.
3. With **less than 1000€, almost each of the hydrants (only one at a time) can be improved to almost the maximum possible improvement reachable with DN150 pipe upgrade:** it can be noticed, indeed, that these hydrants' residual pressure doesn't effectively improve anymore once **1000€ of Total Cost** is reached.
4. Rehabilitation is optional for the majority of the hydrants, but, generally, **4** or **5 replacements** can actually improve hydrants performance
5. Rehabilitation is **mandatory** for Hydrant 2 and Hydrant 55 that result not to delivery adequate flow in **Scenario condition:** pipe replacement is required.

In the next page:

Figure 41: Sets of optimal pipes to change per hydrant in Scenario condition (optimal sets of Decisional Variables).

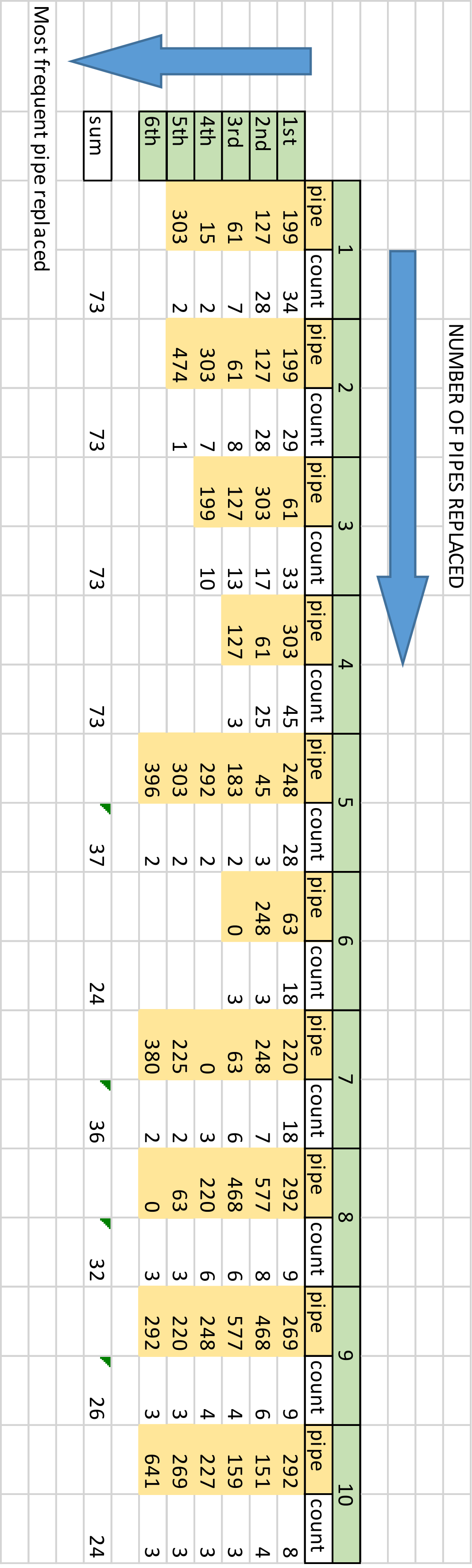
In the Figure, Hydrants 2 and 55 are highlighted in yellow.

	Sets of optimal pipes to change per hydrant in Scenario condition									
Hydrant	1st pipe	2nd pipe	3rd pipe	4th pipe	5th pipe	6th pipe	7th pipe	8th pipe	9th pipe	10th pipe
1	127	199	61	303	476	17	475	478	489	483
2	15	199	127	61	303	17	478	248	475	489
3	127	199	303	61	248	227	225	292	269	636
4	199	303	127	61	443	538	5	442	532	133
5	61	127	199	303	248	63	220	577	468	292
6	61	127	199	303	248	63	220	577	468	292
7	127	199	61	303	248	63	220	136	541	292
8	127	199	61	303	439	552	40	218	63	220
9	199	127	61	303	385	248	63	220	292	269
10	199	127	303	61	248	145	312	251	249	186
11	127	199	61	303	358	248	63	220	292	269
12	199	127	61	303	422	430	120	423	56	420
13	127	199	61	303	248	558	76	145	292	269
14	199	127	61	303	627	248	63	220	577	468
15	199	61	303	127	248	63	220	292	269	227
16	127	61	199	303	248	577	63	220	468	151
17	127	199	61	303	248	577	63	220	468	151
18	199	127	61	303	248	451	648	63	220	612
19	127	61	199	303	186	145	248	101	270	293
20	199	127	61	303	248	292	269	102	268	561
21	199	303	127	61	208	75	439	552	40	218
22	199	127	303	61	248	451	63	220	612	519
23	199	61	127	303	248	227	225	292	269	636
24	127	199	61	303	45	0	0	0	0	0
25	127	199	303	61	45	0	0	0	0	0
26	303	127	199	61	292	269	248	272	130	301
27	127	199	61	303	45	0	0	0	0	0
28	127	199	61	303	292	269	248	272	130	301
29	199	127	61	303	102	268	559	302	248	145
30	199	127	303	61	183	643	248	88	595	322
31	127	199	303	61	248	63	220	292	269	577
32	127	199	61	303	183	310	643	308	307	595
33	303	127	199	61	328	568	329	110	325	248
34	199	303	127	61	248	63	220	577	468	292
35	61	127	199	303	248	63	220	468	577	292
36	61	199	127	303	174	594	88	369	370	632
37	199	127	61	303	248	63	220	468	577	292
38	199	127	61	303	248	63	220	468	577	292
39	127	199	61	303	355	378	86	577	97	397
40	199	127	61	303	85	354	355	378	86	577
41	199	127	303	61	117	358	248	574	363	575
42	199	127	61	303	369	632	367	577	248	151
43	127	199	303	61	372	375	359	373	371	369
44	127	199	61	303	351	376	352	577	396	91
45	199	61	127	303	390	51	393	421	159	602
46	127	199	303	61	248	63	220	468	421	159
47	199	127	61	303	119	391	415	395	248	416
48	199	127	61	303	412	50	403	408	414	248
49	127	199	61	303	416	33	511	423	56	420
50	61	303	199	127	248	63	220	468	421	159
51	199	127	303	61	248	63	220	292	269	641
52	127	199	61	303	136	541	248	63	220	552
53	127	199	303	61	450	6	551	525	126	63
54	199	127	303	61	467	121	468	486	19	497
55	15	474	199	61	303	127	17	478	248	475
56	199	303	127	61	16	480	248	477	63	220
57	199	127	303	61	248	63	220	292	269	641
58	61	199	127	303	248	63	220	292	269	641
59	61	199	127	303	487	497	496	507	20	26
60	199	61	127	303	248	63	220	292	269	227
61	127	61	199	303	501	503	27	24	510	499
62	199	127	61	303	508	29	612	26	506	616
63	199	303	127	61	519	517	190	573	650	36
64	199	127	61	303	248	63	220	292	269	227
65	199	61	127	303	248	525	126	63	220	551
66	127	199	303	61	576	151	577	152	472	9
67	127	199	303	61	396	91	380	382	89	385
68	127	199	303	61	396	91	380	382	89	385
69	127	199	61	303	425	122	428	95	426	400
70	199	303	61	127	248	63	220	468	421	159
71	199	127	61	303	607	2	542	550	453	81
72	127	199	61	303	248	63	220	577	468	292
73	199	127	61	303	640	168	632	577	576	151

Figure 42: Most frequent replaced pipes.

The chart on the right shows the most frequent pipes that result to be replaced by Algorithm, regarding **all hydrants.** Many considerations can be done on this chart along with Pareto Sets in Figure 40: for example, it can be seen how **consistent** residual pressure improvements occur until **4** or **5** pipes are replaced: further replacements don't give appreciable improvements. **The most frequent pipes to be consistently replaced by Algorithm** result to be the following, sorted by total count in all MOOPs:

1. **Pipe 199:** 73 times
2. **Pipe 61:** 73 times
3. **Pipe 303:** 73 times
4. **Pipe 127:** 72 times
5. **Pipe 248:** 35 times
6. **Pipe 63:** 27 times
7. **Pipe 292:** 20 times



	1		2		3		4		5		6		7		8		9		10	
	pipe	count	pipe	count	pipe	count	pipe	count	pipe	count	pipe	count	pipe	count	pipe	count	pipe	count	pipe	count
1st	199	34	199	29	61	33	303	45	248	28	63	18	220	18	292	9	269	9	292	8
2nd	127	28	127	28	303	17	61	25	45	3	248	3	248	7	577	8	468	6	151	4
3rd	61	7	61	8	127	13	127	3	183	2	0	3	63	6	468	6	577	4	159	3
4th	15	2	303	7	199	10			292	2			0	3	220	6	248	4	227	3
5th	303	2	474	1					303	2			225	2	63	3	220	3	269	3
6th									396	2			380	2	0	3	292	3	641	3
sum		73		73		73		73		37		24		36		32		26		24

When talking about Hydrants 2 and 55, they need to be **rehabilitated.**

But, talking about other Hydrants, they actually only need to be improved, and in a general view of investing money on **improving firefighting capacity of WDN, the Pipes just listed should be chosen to be replaced to consistently and robustly improve the overall WDN's firefighting capacity.**

MOOP for **Hydrant 15** exactly gives these **set of optimal decisional variables,** so it could represent an **average improvement intervention for all hydrants in the network: replacing this set of pipes could lead a <u>5 ~ 10m gain in residual pressure to ALL hydrants contemporarily</u>.**

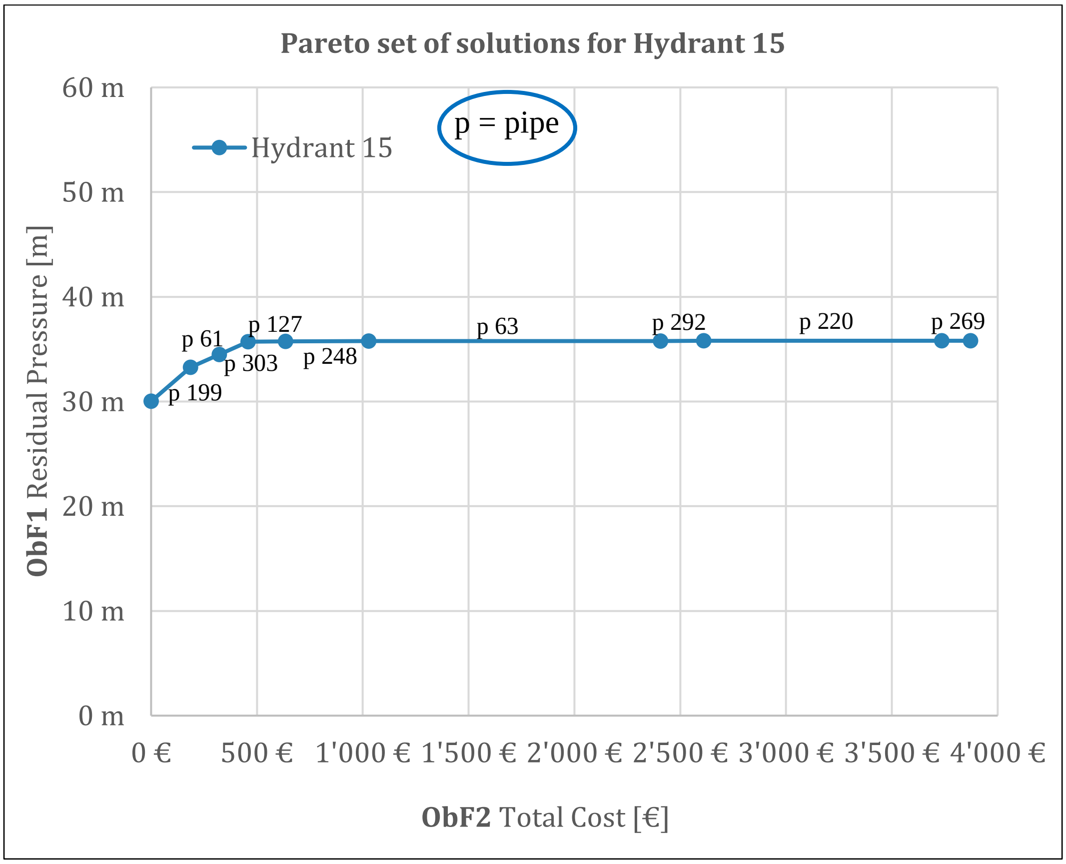


Figure 43: Average hydrants improvement.

Anyway, for majority part of the network this is an improvement intervention and not actually a rehabilitation one: this could be due to 3 main facts:

1. The Case Study's WDN itself is a very **redundant** one**:** when **many loops** make the network so redundant, a node can very easily and effectively be supplied with water from different directions, even in **critical conditions,**
2. Only DN150 pipe upgrade is being dealt with, in this work, as Decisional Variables, for simplicity,
3. Hydrants (apart from Hydrants 2, 55) have already good performance, so one can't expect very high improvements.

Moreover these pipes can be located in WDN in **Figure 45** to discover another interesting thing: the very first **four pipes,** which lead to the major improvements in **residual pressure gain, namely Pipes 199, 61, 303, 127** are the **most upstream ones** and they are very short in length.

This could suggest that the whole upstream part of this DMA may be a bit under-sized with respect of firefighting or critical events in general (see Paragraphs 2.1 & 3.2.3).

Further pipes (248, 63, 292) are more casually located in WDN, but actually they don't lead to very high improvements.

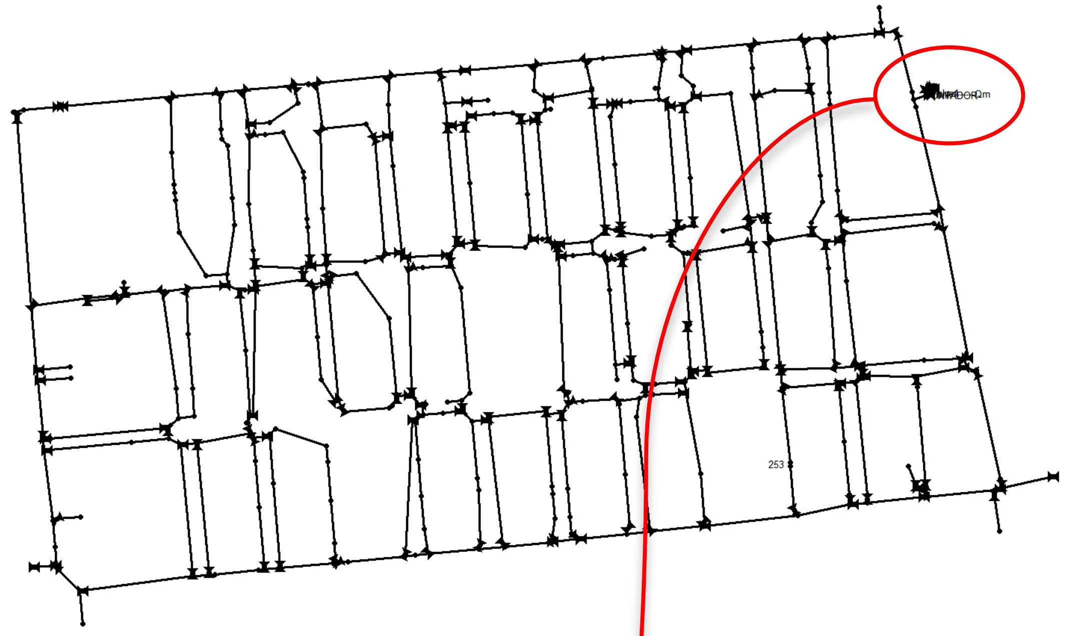
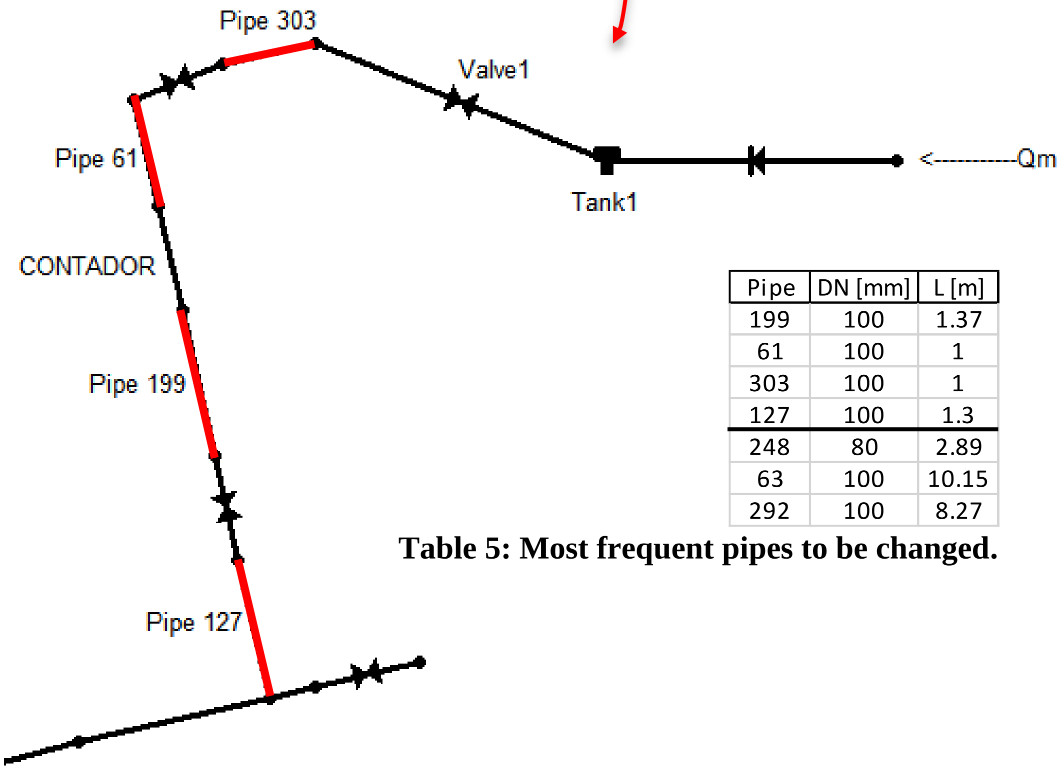


Figure 44: Epanet WDN overview.



Pipe	DN [mm]	L [m]
199	100	1.37
61	100	1
303	100	1
127	100	1.3
248	80	2.89
63	100	10.15
292	100	8.27

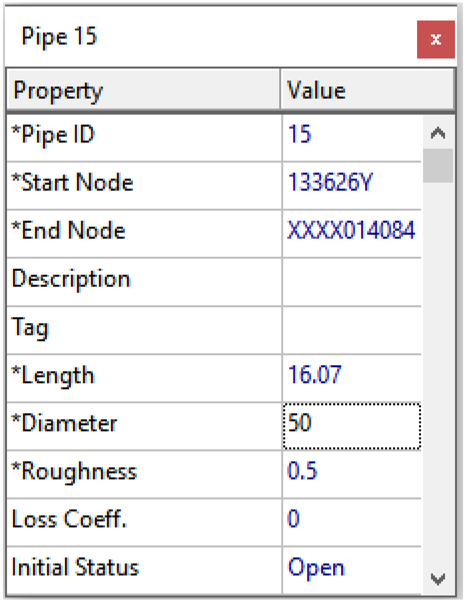
Table 5: Most frequent pipes to be changed.

Figure 45: Upstream DMA mains.

REHABILITATION OF HYDRANT 2 AND HYDRANT 55

These Hydrants need to be **rehabilitated** since they miss minimum requirements: actually, just changing **Pipe 15** (**Figure 46**) results in **rehabilitating both of them.**

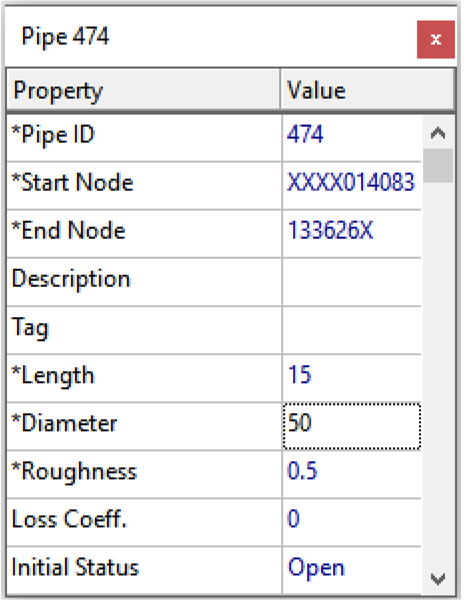
Then changing Pipe 474 (**Figure 47Error! Reference source not found.**) and, again Pipes 199, 61, 303 and 127 hydrants performance can be furtherly improved.



Property	Value
*Pipe ID	15
*Start Node	133626Y
*End Node	XXXX014084
Description	
Tag	
*Length	16.07
*Diameter	50
*Roughness	0.5
Loss Coeff.	0
Initial Status	Open

Figure 46: Pipe 15 properties.

Basically, it can be seen that **Pipes 15 causes issues to hydrants:** this is because it is too small to correctly supply water in critical condiions.

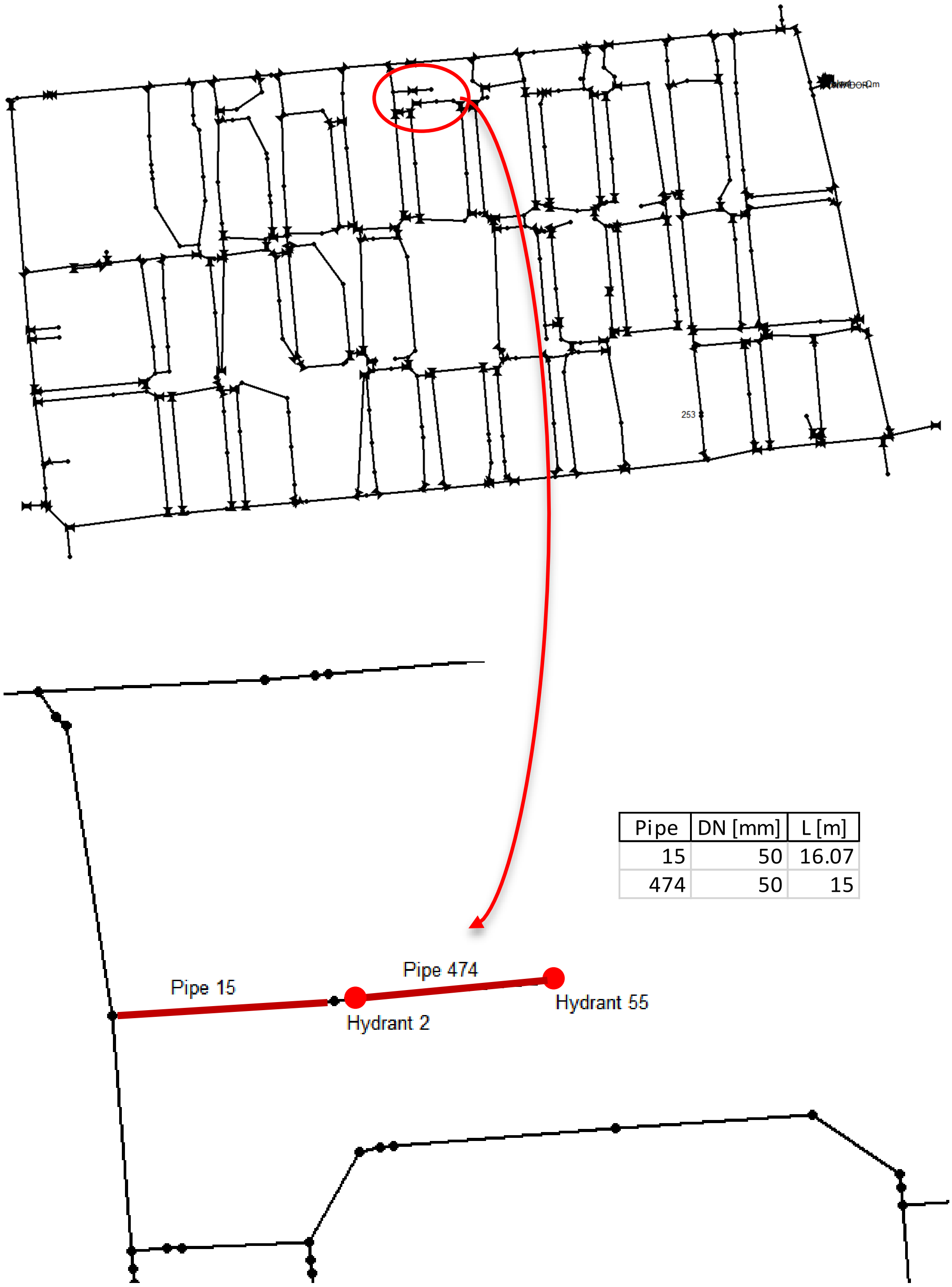


Property	Value
*Pipe ID	474
*Start Node	XXXX014083
*End Node	133626X
Description	
Tag	
*Length	15
*Diameter	50
*Roughness	0.5
Loss Coeff.	0
Initial Status	Open

Figure 47: Pipe 474 properties.

In **Figure 48** Hydrants 2, 55 and Pipes 15, 474 can be located in the WDN.

In **Figure 49 Pareto Sets of optimal solutions** for Hydrants 2, 55 are shown.

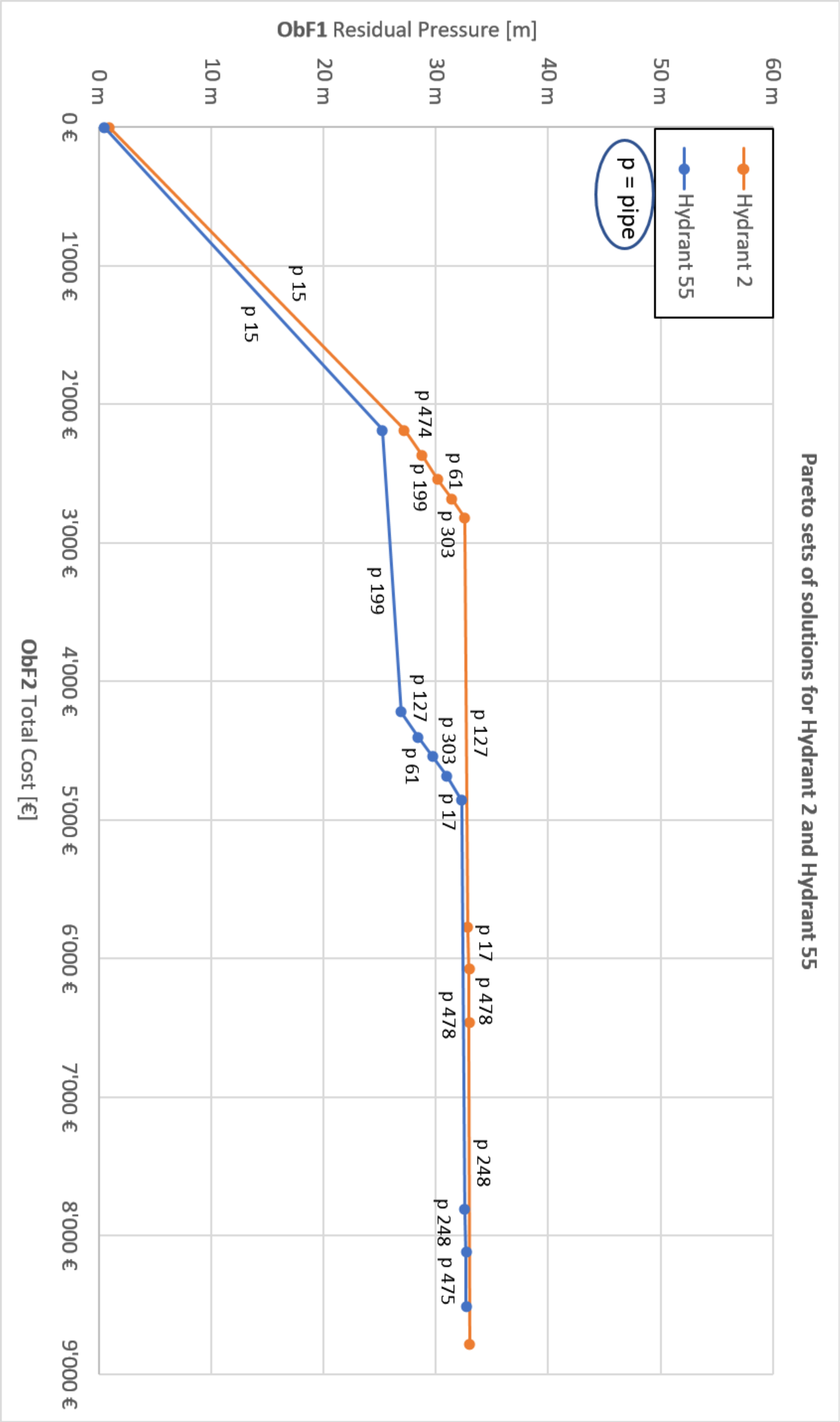


Pipe	DN [mm]	L [m]
15	50	16.07
474	50	15

Figure 48: Pipes 15, 474 location.

In the next page:

Figure 49: Hydrants 2,55 Pareto Sets of optimal solutions.


Pareto sets of solutions for Hydrant 2 and Hydrant 55
Hydrant 2
Hydrant 55
p = pipe
ObF1 Residual Pressure [m]
0 m
10 m
20 m
30 m
40 m
50 m
60 m
ObF2 Total Cost [€]
0 €
1'000 €
2'000 €
3'000 €
4'000 €
5'000 €
6'000 €
7'000 €
8'000 €
9'000 €
p 15
p 15
p 474
p 61
p 199
p 303
p 199
p 127
p 127
p 303
p 61
p 17
p 17
p 478
p 478
p 248
p 248
p 475

7.2 Future developments

It is worth to notice something:

1. Case Study's WDN doesn't allow to show very significant results due to its **redundancy:** it has so many loops and its overall behavior, even in critical conditions, is already quite good,
2. Usually, algorithm indicates that the best pipes to change (apart from those that are the most upstream pipes) are some of those that are near the hydrant: this could, again, due to Point 1.

In spite of Point 1 and Point 2, the **Rehabilitation Methodology** could still be very useful when **decision makers** deal with really **deficient network,** that show to have real deficiency in hydrants performance and in network piping.

Furthermore, even if a WDN has a worse behavior or a worse network piping, just because of the fact that WDNs are usually looped, this MOO rehabilitation methodology approach, as stated in this work, could be a **useful tool for decision makers:** in particular, **Pareto Sets of Decisional Variables and Pareto Fronts of near-optimal solutions** could be a practical **tool** in deciding **rehabilitation** or **improvements interventions.**

FUTURE DEVELOPMENTS

Algorithms

Greedy Algorithm developed for this work could be compared and **benchmarked** with **NSGA-II** to prove the former's effectiveness and reliability.

Decisional Variables

Decisional Space should be extended to further **diameters of pipes** to maybe find even better **near-optimal sets of solutions.**

Water age

In this work only firefighting aspect has been tackled but, since a pipe related rehabilitation methodology has been conducted, also **water quality analysis may be run** in future, because it is known that pipe enlargement can cause water quality problems during normal network operation [18]. In particular, **water age** is a major factor in water quality deterioration since it implies chlorine residual concentration reduction and disinfection byproduct (DBP) formation [123].

Robust MOO

More generally, uncertain parameters and variables can affect the estimation of hydraulic and chemical processes that are mainly model-based ([124], [125], [126]) [28] and so, their results. Water demand is one of the main recognized sources of uncertainty [28]:

1. Consider **probabilistic users demand** instead of deterministic one, like [69] suggests,
2. Consider **hydrant NFF as an uncertainty** itself: varying NFF could cause Pareto fronts to change because more pipes are needed to be changed (more costs) to meet minimum requirements. NFF uncertainty is not considered indeed, but future development could be to consider it, following the lead of [28].

A **Robust MOOP** could be stated basing on such considerations.

Other developments

1. Improve network model calibration: the real network elements operation knowledge could be enhanced and promoted to better run analyses,
2. Do more research on NFF an apply ISO method specifically to municipalities,
3. Improve the evaluation of the cost function used for pipe replacing, maybe using a more recent one.
4. Investigate the case in which more than one hydrant work simultaneously: a probabilistic analysis of which hydrants may be contemporarily used, based on possible fire location considerations, may be led.

7.3 Operation

Applying Methodology for Operation to Benalúa's WDN Case Study, a lot of artificial data have been produced.

To consider the already available firefighting capability of the WDN, hydrants' maximum discharge capacity analysis has been conducted, and the results are shown below.

Hydrant n.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Max flow [L/s]	38	14	44	75	84	42	44	74	38	46	38	72	98	70	42	81	82	92	
Hydrant n.	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
Max flow [L/s]	93	45	39	86	102	46	46	47	45	100	44	36	76	36	39	42	42	52	
Hydrant n.	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	
Max flow [L/s]	83	42	38	32	34	38	33	32	62	41	63	37	75	83	37	88	64	73	
Hydrant n.	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73
Max flow [L/s]	10	36	84	39	58	40	73	79	75	41	87	70	45	32	37	42	75	42	38

Table 6: Hydrants' maximum discharge capacity.

Average	55
Min	10
Max	102
St.Dev.	21.80682
CV	0.393283
Mode	-
Median	45

The **average value** has been assumed as

$$\boldsymbol{F = 55L/s}$$

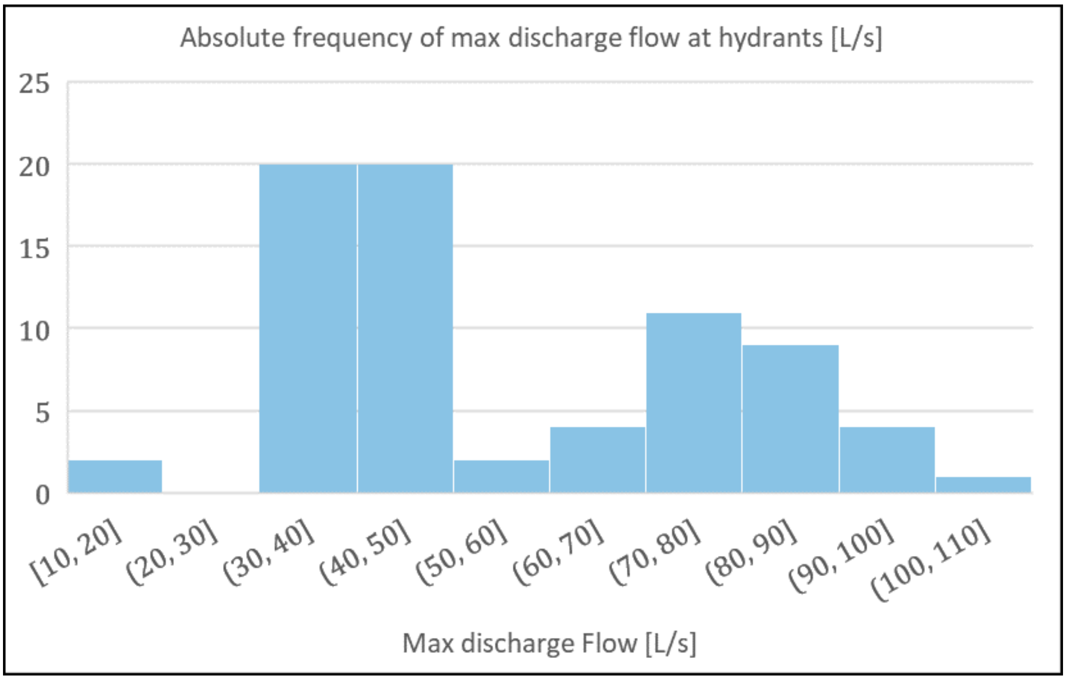


Figure 50: Absolute frequency of max discharge flow at hydrants.

Buildings in Benalúa’s have been assumed to have from **3 to 8 floors** and **Area [ft^2]** has been roughly evaluated on QGIS software with an Area evaluation tool.

max n of floors		max Area
8		50000
min n of floors		min Area
3		1000

Combining all coefficient together, 1200 probable NFF values have been generated, basing on what has been said in Methodology.

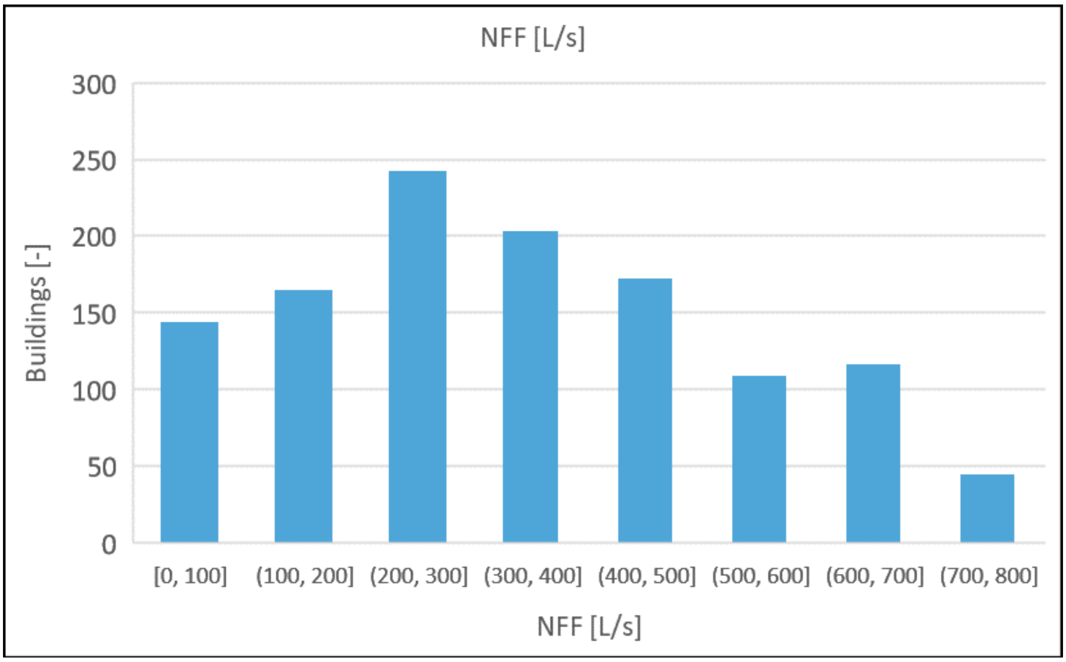


Figure 51: Probable NFF basing on Benalúa’s characteristics.

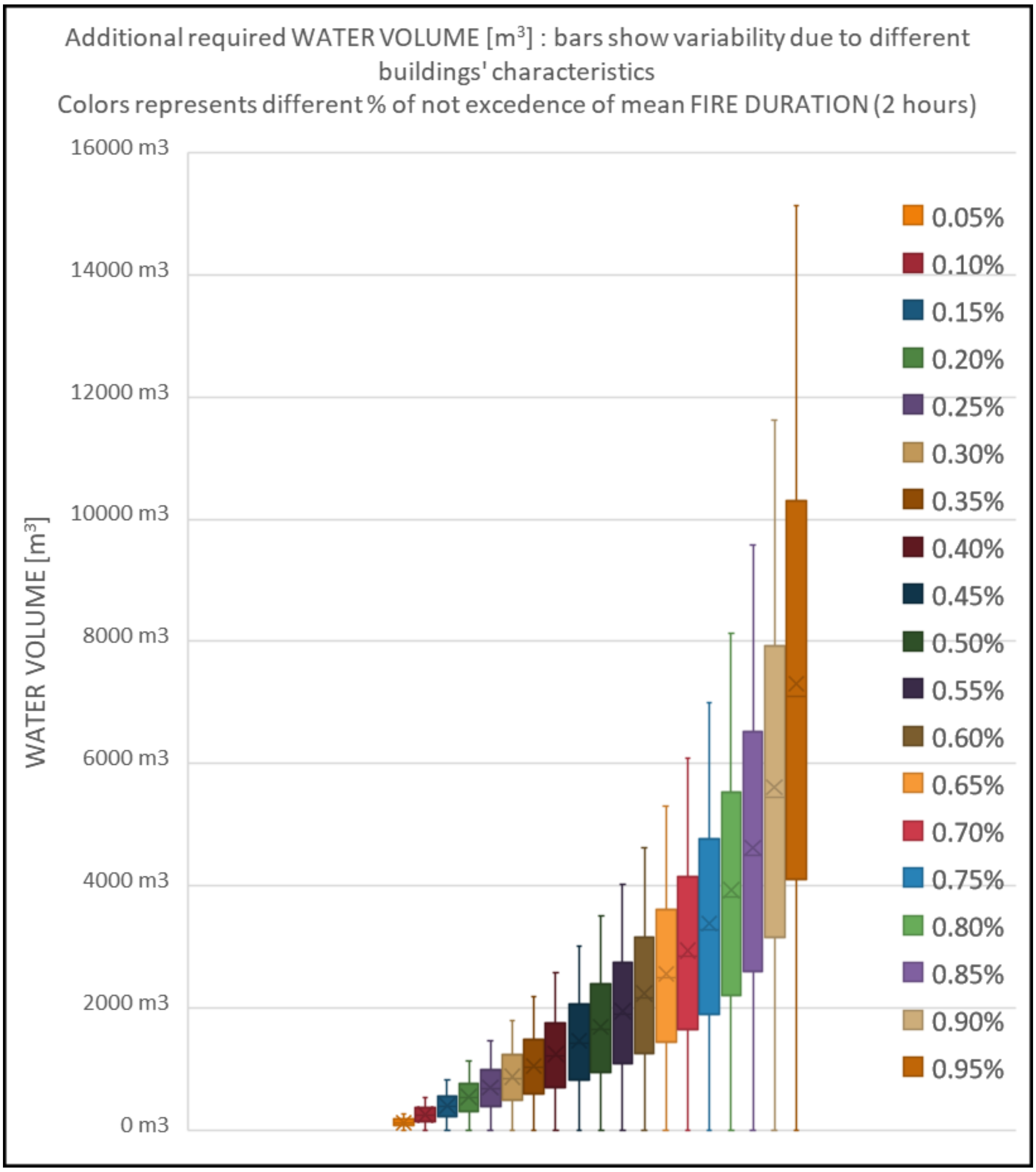


Figure 52: Additional required water volume [m^3].

Finally, **Figure 52** can be obtained: it gives probable **Additional Needed Water ANW** in **[m^3]** depending on probability of not exceedance of the mean Fire Duration $\boldsymbol{d = 2\ hours}$.

8 CONCLUSIONS

In this Chapter a summary of this thesis and final considerations about practical implications of this work are presented along future developments.

This work mainly dealt with the issue of firefighting in urban environment, taking care of investigating the behavior of a potable water supply network when called to be used for fire managing and extinguishing purposes. Because of fire events uncertainty, firstly related to location of occurrence and buildings involved, and because many attentions have to be paid in investing public funding, a Multi-Objective Optimization approach was used to tackle the problem of deficient networks Rehabilitation and a probabilistic approach, instead, was used to tackle the problem about Operation of networks when critical events like fires take place.

Rehabilitation Problem was faced thanks to software implementing a Greedy Algorithm that aimed to find Pareto Fronts containing near-optimal sets of pipes in the network that could be replaced, trading-off total costs, in order to restore firefighting capability of the whole network or of single hydrant too.

Operational Problem, then, was faced considering ISO guide for WDN firefighting capacity assessment, as lead to generate an artificial amount of data about probable Additional Needed Water to supply the network in case of critical fire.

Many additional sides of MOOP formulating, also could be faced, principally because of the Optimization topic’s hugeness and the author wishes to be able to explore them in future works: some of them could be water quality analysis, probabilistic demand analysis, uncertainty analysis, robustness formulation and robust optimization.

Furthermore, important progress has recently be done, and is still being, on Pressure Driven Analysis issue: a more correct, as well as difficult to mathematically and software implement, technique to better analyze deficient networks that could lead, in the future, to more efficiently tackle issues and problems about WDSs.

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10 APPENDICES

APPENDIX 1: PYTHON SCRIPT

Here is reported the Python 3.7.4 script ” OPTIMAL WDN PIPE REPLACING TOOL” specifically written for the purpose of this thesis by the author of this latter, in the period from October 2019 to February 2020. It only has research and educational purposes and it is not intended to be sold or used for other aims. It has not even been published or released anywhere but in this thesis itself.

Please ask the author before using, copying, or giving this code or parts of it to thirds.

Due references, citations and acknowledgements are made throughout the thesis’ text and in the code itself to firstly thank developers and to secondly address the reader to the different sources that helped the author in writing and running the code.

```
# -*- coding: utf-8 -*-
# =========================================================================== #
#                      ---OPTIMAL WDN PIPE REPLACING TOOL---                  #
# =========================================================================== #

--> Created on October 2019.

--> Last updated on February 2020.

@author: Alessandro Farina
   mail: alessandrofarina.eng@gmail.com

This is an algorithm for OPTIMAL PIPE REPLACING in order to rehabilitate a WDN
with a Fire Protection service and meet minimum requirements.
The algorithm's core takes inspiration from
prof. Leonardo Alfonso Segura's Loop for Optimal valve Configuration Algorithm (LOC).

                        This algorithm is also based on:

 ---> Epanet 2.2 beta.1         by USEPA (Pressure Driven Analysis implemented)

 ---> wrapper for python 3 (epamodule.py):             by Open Water Analytics
      it calls the Epanet TOOLKIT functions
      in python through the "epanet2.dll"
"""
#####################################################   MODULES IMPORTING   ###

import epamodule as em   ###  Epanet python wrapper that calls "epanet2.dll" of the Epanet 2.2 TOOLKIT
import numpy as np
import time
import os
import pandas
import math
```

```
#=============================================================================#

####===============       INPUT FILES AND PARAMETERS       ================####

#=============================================================================#
                                               #read carefully to avoid messy

network        = 'network_PDA'
emitter_coeff  = 'hydrants'
demand         = 'single_hydrants'   ### choose between "single_hydrants" and "hydrants_scenarios": the latter
                                     ### file contains
                                     ### different scenarios of 4 hydrants working together
pipes          = 'pipes'

duration   = 2
Base_Leaks = 4### --------> demand PATTERN for nodes to set at line 215
Leaks_2017 = 5

tank_level = 0.1 # [m]   default=1.4m   It's the initial water level in Tank1.


###________________GUMBEL Cumulative Distribution Function__________________###

PROB = 100 # [%] is the probability of not excedance of the GUMBEL CDF for Peak coefficient

### select PROB = 57% for Peak coefficient = 1  --> average condition
### select PROB = 0% to simulate no user demand in the network
### select PROB = 100% to simulate the worst case of user demand

meanCP  = 1                        # Gumbel CDF parameters
stdevCP = 0.465153688              #
modeCP  = meanCP - 0.45*stdevCP    # Do not change these values
alfa    = math.pi/stdevCP/(6**0.5) #
```

```
if   PROB<=0:   Peak = 0
elif PROB>=100: Peak = 2.5
else:
    Peak = modeCP-math.log(math.log(100/PROB))/alfa   ### GUMBEL CDF


fire_event    = 2     ### the fire events you want to explore  (There are 73 hydrants and 34 scenarios)

FLOW = 32/1.25 # [L/s]      ### demand at single hydrant___set =0 if you want to check standard pressures in
                            ### the network
          ###  32 L/s is the minimum for non-sprinklered buildings (AWWA, 2008)
          ###  !!NOTE!! 1,25 is to take into account that Leaks are being considered on Base Demands
          ###  !!Don't remove or change 1,25 !!Only change former value!!

max_LOC_loops = 10      ### max pipes changes you want to check. Set "1" if you only want to check only
                        ### pressures!

UPGRADE = 150 # DN [mm] ### diameter that will replace the original one: DN150 it's the most used one
                        ### in networks that also provide firefighting protection
def cost(L):
    result = (0.00000062*UPGRADE**3 + 0.00025083*UPGRADE**2 + 0.39050539*UPGRADE + 69.63314954)*L  ## [€/m/mm]
( TRICARICO )
    return result

#######          ----select between "single" or "group" at line 265----        ###########

  ##########    ----select also "mode" = "n_pipe" or "1" at line 291----   ###########


###_________________________Reading files section___________________________###

net         = 'INPUT\\'+network+'.inp'
```

```
rep         = 'INPUT\\'+network+'.rpt'

coeff_file  = 'INPUT\\'+emitter_coeff+'.xlsx'

demand_file = 'INPUT\\'+demand+'.xlsx'

pipes_file  = 'INPUT\\'+pipes+'.xlsx'

print('\n')
print('Fire duration: ',duration,' hours.',sep='')
print('Initial water level in Tank: ',tank_level,'m.',sep='')
print('Probability of not excedance of demand: ',PROB,'%.',sep='')
print('Initial water level in Tank: ',tank_level,'m.',sep='')
print('Peak demand coefficient: ',round(Peak,2),'.',sep='')
print('Fire event: ',fire_event,'.',sep='')
print('Hydrant required flow: ',int(FLOW*1.25),'L/s.',sep='')
print('Max LOC loops: ',max_LOC_loops,'.',sep='')
print('Pipe diameter upgrade: DN',UPGRADE,'.',sep='')

print('\nReading files, please wait...')

coeff    = pandas.read_excel(coeff_file)
emitters = np.matrix(coeff)
n_hid    = np.size(emitters, axis=0)

demands  = pandas.read_excel(demand_file)
demand_generated = np.matrix(demands)
n_gen    = np.size(demand_generated, axis=0)

pipes_   = pandas.read_excel(pipes_file,index_col=0)
```

```
############################################   START OF SIMULATION   ##########

em.ENopen(net,rep)

n_node = em.ENgetcount(em.EN_NODECOUNT)
n_tank = em.ENgetcount(em.EN_TANKCOUNT)
n_link = em.ENgetcount(em.EN_LINKCOUNT)
n_patt = em.ENgetcount(em.EN_PATCOUNT)
n_curv = em.ENgetcount(em.EN_CURVECOUNT)
n_cont = em.ENgetcount(em.EN_CONTROLCOUNT)

n_junc = n_node - n_tank

n_pipe   = 0
for i in range(1,n_link+1):
    if em.ENgetlinktype(i)==1:
        check=1
    else:
        check=0

    n_pipe = n_pipe+check

n_CVpipe = 0
for i in range(1,n_link+1):
    if em.ENgetlinktype(i)==0:
        check=1
    else:
        check=0

    n_CVpipe = n_CVpipe+check

n_PRV    = 0
for i in range(1,n_link+1):
```

```
    if em.ENgetlinktype(i)==3:
        check=1
    else:
        check=0

    n_PRV = n_PRV+check

n_PBV    = 0
for i in range(1,n_link+1):
    if em.ENgetlinktype(i)==5:
        check=1
    else:
        check=0

    n_PBV = n_PBV+check

if n_junc != np.size(emitters, 1):
    print('Number of junctions is {}: it is wrong! Try with another file.\n'.format(n_junc))

if n_junc != np.size(demand_generated, 1):
    print('Number of junctions is {}: it is wrong! Try with another file.\n'.format(n_junc))


# print("\nNUMBER OF JUNCTIONS IS: {}".format(n_junc))
# print("NUMBER OF LINKS IS: {}".format(n_link))

# print('NUMBER OF PRV VALVES IS: {}\n'.format(n_PRV))
# print('NUMBER OF PIPES IS: {}\n\n'.format(n_pipe+n_CVpipe))




t0=time.time()
```

```
###__________________INITIALIZING PIPES MATRIX FOR LOOPS____________________###

new       = np.array(pipes_)
pp_origin = np.zeros((n_pipe,len(new[0])))
pp_origin += new

for i in range(n_pipe-1):                ### Generates the pipes configuration matrix: THE FIRST ROW IS THE
                                         ### REFERENCE
        if pp_origin[i+1,i]  < UPGRADE:
            pp_origin[i+1,i] = UPGRADE
        else:
            pass

####################   OBJECTIVE FUNCTIONS DEFINITIONS AND OUTPUT SETTING   ###

Pressures  = np.zeros((fire_event, n_junc)) # Pressures at all nodes
#Demands    = np.zeros((n_pipe, n_junc)) # Demands at nodes (if Pressure Driven is used)
#Flows_link = np.zeros((n_pipe, n_link)) # Flows in all links


F          = np.zeros((n_pipe,1))         ### gives the residual PRESSURE at hydrant that is working

incremento = np.zeros((n_pipe,1))         ### gives the residual PRESSURE increment at hydrant that is working

Function   = np.zeros((n_pipe,1))         ### TEMPORARY OBJECTIVE FUNCTION INSIDE THE LOOP. AT EACH LOOP IS THE
                                          ### BEST SOLUTION

D          = np.zeros((n_pipe,1))         ### OF gives the actual DEMAND at hydrant that is working (HAS TO BE
                                          ### INCREASED)

Cost       = np.zeros((n_pipe,1))         ### retrieves cost for replacing i-th pipe

pressure   = np.zeros((fire_event,max_LOC_loops+1)) ### summary of pressures at all hydrants at different loops
```

```
Hydr_flow  = np.zeros((fire_event,max_LOC_loops+1))  ### summary of outflow at all hydrants at different loops

gain       = np.zeros((fire_event,max_LOC_loops+1))  ### summary of pressures gains at all hydrants at
                                                     ### different loops

price      = np.zeros((fire_event,max_LOC_loops+1))  ### summary of prices for changing pipes at different
                                                     ### loops

resume     = np.zeros((fire_event,max_LOC_loops))    ### a matrix that will store the optimal changes for every
                                                     ### fire event

#_____________________________________________________________________________________________________________#


##########################################################   INITIALISING   ###

base_demands=[]

for i in range (1,n_junc+1):
    base_demands.append(em.ENgetnodevalue(i,em.EN_BASEDEMAND))  ### retrieves base demands at all nodes

em.ENsettimeparam(em.EN_DURATION,duration*60*60)             ### set duration of the simulation from time 00:00

for i in range(1,n_junc+1):               ### set demand pattern at all nodes except for the network inlet node
    if not i==em.ENgetnodeindex('Node1'):
        em.ENsetnodevalue(i, em.EN_PATTERN, Base_Leaks)

em.ENsetnodevalue(em.ENgetnodeindex('Tank1'), em.EN_TANKLEVEL, tank_level)
```

```
#                                     ALGORITHM STARTING                                                      #
#_____________________________________________________________________________________________________________#

single = fire_event
group  = 1

for g in range (n_pipe):
    if not g==0:
        Cost[g,0] = cost(em.ENgetlinkvalue(g, em.EN_LENGTH))     ### RETRIEVES COST IN € FOR REPLACING PIPE g

for hydrant_scenario in range(single,fire_event+1):     ### switch between "single" and "group" to analyze the
                                                        ### single event or all the hydrants together

    print ('\n\n'+24*' '+'Hydrant scenario n.{}'.format(hydrant_scenario))

    increment = np.zeros((n_pipe,1))     ### pressure increment at each configuration

    for i in range(1,n_junc+1):          ### sum the user demands and the hydrant demand at all nodes
        if not i==em.ENgetnodeindex('Node1'):
            em.ENsetnodevalue(i,em.EN_BASEDEMAND,Peak*base_demands[i-1]+FLOW*demand_generated[hydrant_scenario-1,i-1])
                                                        ### set hydrant demnads depending on the open hydrant
        #########
            # em.ENsetnodevalue(i,em.EN_BASEDEMAND,Peak*base_demands[i-1])
            # em.ENsetnodevalue(i,em.EN_EMITTER,emitters[hydrant_scenario-1,i-1])
        #########                                       ### set emitters values depending on the open hydrant

    pp=pp_origin.copy()  ## This is because otherwise, also original matrix would be changed !! slice [:] does
                         ## not work!

    where=-1

    increment = 100
```

```
P=0
while increment>0.01 and P<max_LOC_loops:      ### increment = [m]
    P += 1
    print('\n'+10*' '+'Loop {} evaluating...'.format(P),end='')

    mode = n_pipe ### default: "n_pipe". Switch to "1" if you want to only check initial hydrants pressures

    for g in range (mode):   ### set pipe diameters: in each "g" configuration only 1 pipe has been changed

        for index in range(1,n_pipe+1):
            em.ENsetlinkvalue(index, em.EN_DIAMETER, pp[g,index-1])

        em.ENopenH()          ###  Epanet 2.2 by USEPA
        em.ENinitH(0)         ###  Epanet wrapper for python by Open Water Analytics
        step = 1

        while step > 0:

            err = em.ENrunH()
            step = em.ENnextH()

            if err:
                print(hydrant_scenario, step, err)

            # for i in range (1,n_junc+1):
            #     Pressures[g, i-1] = em.ENgetnodevalue(i, em.EN_PRESSURE)

            #for k in range (1,n_junc+1):
            #    Demands[g, k-1] = em.ENgetnodevalue(k, em.EN_DEMAND)

            #for h in range (1, n_link+1):
            #    Flows_link[g, h-1] = em.ENgetlinkvalue(h, em.EN_FLOW)
        slide = 0
```

```
            while emitters[hydrant_scenario-1,slide]==0:
                slide += 1       ### hydrant's position in the matrix

            F[g,0]    = em.ENgetnodevalue(slide+1, em.EN_PRESSURE)   ### RETRIEVES      PRESSURE      AT
HYDRANT FOR EACH CONFIGURATION g ###
            incremento[g,0] = F[g,0]-F[0,0]                          ### RETRIEVES PRESSURE INCREMENT AT
HYDRANT FOR EACH CONFIGURATION g ###
            D[g,0]    = em.ENgetnodevalue(slide+1, em.EN_DEMAND)     ### RETRIEVES   ACTUAL DEMAND    AT
HYDRANT FOR EACH CONFIGURATION g ###


            if not g==0:
                Function[g,0] = incremento[g,0]/Cost[g,0]

            em.ENcloseH()   ### pay attention when indenting or unindenting !!! Must use it, otherwise memory
will not be freed!!


        maximum_F        = float(max(F))
        where_F          = np.where(F==maximum_F)[0]

        increment        = maximum_F - F[0,0]

        maximum_Function = float(max(Function))
        where_Function   = np.where(Function==maximum_Function)[0]

        maximum_D        = float(max(D))
        where_D          = np.where(D==maximum_D)[0]


        where = where_Function[0]

        pressure [hydrant_scenario-1,P-1] = maximum_F       ### STORES THE PRESSURE VALUES at each loop
```

```
        Hydr_flow[hydrant_scenario-1,P-1] = maximum_D       ### STORES THE OUTFLOW VALUES at each loop

        gain     [hydrant_scenario-1,P]   = increment       ### STORES THE PRESSURE GAIN VALUES at each loop

        price    [hydrant_scenario-1,P]   = Cost[where,0]   ### STORES THE PRESSURE GAIN VALUES at each loop

        if P==1:
            init=F[0,0]
            print('Initial pressure after ',duration,' hours is: ',round(init,2),'m.\n',sep='',end='\n'+30*' ')
            pressure[hydrant_scenario-1,0]=init



###=========================================================================###

        for m in range(n_pipe):            ###   Loop for Optimal pipe changing (Greedy algorithm)
            pp[m,where-1] = pp[where,where-1]

###=========================================================================###

        if not mode==1:
            print(round(maximum_F,2),'m replacing Pipe "',where,'"',' with DN ',UPGRADE,sep='')
            print('Increment = ',increment,'m')

        resume[hydrant_scenario-1,P-1] = where   ### STORES THE OPTIMAL CHANGES

    #em.ENsaveH()       ### Optionally report saving
    #em.ENreport()
```

```
######################################################### END OF SIMULATION ###
        # print(10*' '+15*'~')
        # print('_______________',em.ENgeterror(err),'\n\n')


    #del pp   ### because it allocates too much memory, causing MemoryError (Solved: it was "em.ENcloseH()"
              ### command)
#=============================================================================#

####=====================       OUTPUT SECTION       ======================####

#=============================================================================#
#### remember to better preventively delete file from any previous analysis ###

    if not mode==1:

        print('\n\n     Initial pressure after ',duration,' hours was: ',round(init,2),'m.',sep='')
        print('\n\n     Total pressure gain, changing ',max_LOC_loops,' pipes, is: ',round(maximum_F -
init,2),'m.',sep='')
        print('\n\n     Final pressure is: ',round(maximum_F,2),'m.',sep='')

    for i in range (1,n_junc+1):
        Pressures[hydrant_scenario-1, i-1] = em.ENgetnodevalue(i, em.EN_PRESSURE)
          ### Evaluates pressures at all nodes for every hydrant working at a time


#pandas.DataFrame(Flows_link).to_excel('OUTPUT\\'+str(hydrant_scenario)+'Output_Flows.xlsx',header=False,index=
False)

#pandas.DataFrame(Pressures).to_excel('OUTPUT\\'+str(hydrant_scenario)+'Output_Pressures.xlsx',header=False,ind
ex=False)
#pandas.DataFrame(Demands).to_excel('OUTPUT\\'+str(hydrant_scenario)+'Output_Demands.xlsx',header=False,index=F
alse)
```

```
    #pandas.DataFrame(OF_1).to_excel('OUTPUT\\'+str(hydrant_scenario)+'_OF_1.xlsx',header=False,index=False)
    #pandas.DataFrame(F).to_excel('OUTPUT\\'+str(hydrant_scenario)+'_F.xlsx',header=False,index=False)

#pandas.DataFrame(Hydr_flow).to_excel('OUTPUT\\'+str(hydrant_scenario)+'_Hydr_flow.xlsx',header=False,index=False)

    #pandas.DataFrame(pp).to_excel('OUTPUT\\new_diam.xlsx',header=False,index=False)


#os.startfile('OUTPUT\\new_diam.xlsx')
#os.startfile('OUTPUT\{}_F.xlsx'.format(hydrant_scenario))
if mode==1:
    pandas.DataFrame(pressure).to_excel('OUTPUT\\Hydrants pressures+++.xlsx',header=False,index=False)
    os.startfile('OUTPUT\\Hydrants pressures+++.xlsx')

    pandas.DataFrame(Hydr_flow).to_excel('OUTPUT\\Hydrants flows+++.xlsx',header=False,index=False)
    os.startfile('OUTPUT\\Hydrants flows+++.xlsx')

    pandas.DataFrame(Pressures).to_excel('OUTPUT\\Network pressures+++.xlsx',header=False,index=False)
    os.startfile('OUTPUT\\Network pressures+++.xlsx')

############################################################## TIME ELAPSED ###

t1  = time.time()
t_s = round(t1 - t0,2)
t_m = round((t1 - t0)/60,2)
t_h = round((t1 - t0)/60/60,2)
print ('Time elapsed = {} seconds'.format(t_s))
print ('Time elapsed = {} minutes'.format(t_m))
print ('Time elapsed = {} hours'.format(t_h))
print  ('\n\n'+17*' '+'-- Check output files --\n')

#em.ENclose()
```