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Optimising Pump Scheduling in Water Distribution Systems to Minimize Leakage

Case Study: Water Distribution Network of Braila, Romania

Ammanuel Bekele Tilahun
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Optimising Pump Scheduling in Water Distribution Systems to Minimize Leakage

Master of Science Thesis
by
Ammanuel Bekele Tilahun

Supervisors
Dr. Leonardo Alfonso

Mentors
Dr. Leonardo Alfonso and Professor Dimitri Solomatine

Examination Committee

Professor Dimitri Solomatine
Dr. Leonardo Alfonso
Dr. Mario Castro Gama

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Abstract

Large amount of water is lost every day in water distribution networks (WDN) through leakage. Pressure Management by means of optimal pump operations is one vital way of leakage reduction in water distribution systems. Pumping in WDN can be of two types the first being pumping towards a storage tank which supplies the system by gravity and the second being pumping directly towards the network from storage reservoirs. Several researchers have studied the technique of pump scheduling as an option to minimize leakage in the first kind of systems. However, the inclusion of pressure-driven demand analysis for Real time control optimization in water distribution systems where pumping is done directly towards the pipe network is limited in the current studies. This research addresses this issue by investigating how effective it is to reduce leakage through optimization of pump operation in such systems using a methodology that first determines the location of leaking nodes according to traffic load, diameter of pipes and historical data of failure. These nodes are used during the leakage modeling of the network as points of leakage flow. Another set of nodes, critical nodes, were also determined that are expected to experience large drop in pressure. The constraints of the optimization are designed in such a way that the pressure at these nodes is always above the minimum service pressure in the network. The experimental design includes three categories of tests totaling 13 runs.

The research was applied in the case study area of Braila, Romania water distribution system. Multi-objective genetic algorithm (NSGA II) was used to search for optimal pump scheduling in such a way that the total leakage volume during the simulation time and energy consumption by pumps would be minimal. Pressure driven demand analysis using the EPANET software together with WNTR Python library were utilized to do the hydraulic analysis of the model. Flow emitter properties of EPANET junctions were used to model leakage points in the network as orifices.

Results show that the total leakage volume in the network resulting to the optimal operation of pumps has a reduction of 12 % relative to the existing leakage rate due to the customary operation. Energy consumption by the considered pump has also shown a 9% reduction. The resulting optimal pump schedules indicated that, for this specific network, the pump can be turned off only during night time where the demand is off peak so as to satisfy the minimum service pressure while minimizing leakage volume.

Key Words: Leakage, Pump Scheduling, Genetic Algorithm, Emitters, WNTR

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Abbreviations

ANN	Artificial Neural Network
ARIMA	Auto Regressive Integrated Moving Average
DDA	Demand Driven Analysis
DMA	District Metering Area
GIS	Geographic Information System
ICT	Information Communication Technology
MOO	Multi objective optimization
NRW	Non-Revenue water
NSGA II	Non-dominated Sorting Genetic Algorithm II
PDA	Pressure Driven Analysis
PRV	Pressure Reducing Valves
RTC	Real Time Control
SCADA	Supervisory Control and Data Acquisition
SOO	Single objective optimization
VSP	Variable Speed Pump
WDN	Water Distribution Network
WDS	Water Distribution Systems
WNTR	Water Network Tool for Resilience

Chapter 1 Introduction

1.1 Background

One in three people of the world does not have access to safe drinking water. The rest, which is about 71% of the world uses potable water. Water scarcity is one of the reasons for inability to supply safe water. Nevertheless, large amount of water is lost every day in water distribution networks. According to the World Bank's estimate, "In developing countries, roughly 45 million cubic meters of water are lost daily"(WORLDBANK, 2016) . This is equivalent to an economic value of US$3 billion per year and it would be enough to serve about 200 million people. In water audit terms, the difference between System Input Volume and Billed Authorized consumption is known as Non-Revenue water (NRW) (A.O.Lambert, et al., 2002). Major portion of NRW is physical water loss which is the water wasted underground in the form of leakage from pipe networks. While, the rest accounts for water consumed but not billed due to different reasons.

Leaked water is damaging to the economy both directly and indirectly. In addition to the cost of raw water; power which is applied to treat and pump a bunch of water which will not eventually be used is also a damage. The treatment cost is also significant. Moreover, the water leaked to the ground can cause the soil to sink, causing the foundations of roads and buildings to damage. It also erodes the pipe beddings and leads to more pipe breaks. (Nicolini, et al., 2014)

Basically there are two types of leakages in water distribution networks which are bursts and background leakages. Background leakages are those occurring at joints and fittings having low flow rates and difficult to detect. Whereas, bursts are reported and unreported moderate to high flow leaks due to holes and cracks in the distribution networks (Sharma, 2020).

It is not possible to eliminate all real losses from a distribution system but they can be reduced. The common practice followed by many water utilities to minimize leakage is detecting the leaks and repairing or replacing the pipes. But this technique has its own drawbacks like the fact that it is a very difficult and expensive task. Detecting leaks is costly especially for developing countries. Moreover, repairing and replacement requires traffic diversion to excavate the area and also water service break offs during the replacement which leads to customer dissatisfaction.

Another way of reducing leakage is through pressure management. High pressure in a distribution system is one source of pipe bursts together with other factors like pipe age, external pressure from traffic, loose pipe fittings, low quality material and damage during excavation. Especially, for WDS of flat topographies with high leakage, preesure reduction is the most convenient way to minimize leakage (Walski, et al., 2006).

The amount of leakage in pipes is highly related to the pressure inside the pipes as well. Pipes with high pressure will have greater amount of leakage; whereas in pipes with reduced pressure, the leakage volume is low. Just looking at this correlation, one can suggest to reduce the pressure as low as possible; however the reliability of the water supply to customers must be ensured by maintaining a minimum pressure in the network. In addition, another problem associated with too low network pressure is that it creates a high chance of external contaminants entering the network through the leak openings leading to poor water quality. Therefore, there should be an operational mechanism to optimally reduce the pressure and at the same time satisfying the constraint which ensures the minimum pressure needed to address the demands.

Researchers have tried to come up with different solutions to solve the problem of water leakage in water distribution networks through pressure management. Installation of pressure reducing valves (PRVs) at optimal places is one way of achieving minimization of leakage through pressure management in systems with important elevation differences (Mahdavi, et al., 2011). The research first sets a fixed number of PRVs and tries to find optimal locations of these PRVs that minimize total amount of leakage in WDS.

Pumping optimization or scheduling is also a method proposed by researchers as a mechanism of pressure management for leakage minimization. Traditionally, pumping schedule has been developed considering only minimizing pumping energy cost which results in a schedule of pumping to storage tanks during low tariff hours (usually night time) and the WDN will be supplied by means of gravity from the storage tank during the day. But, this method disregards the fact that water loss increases during low demand hours due to the increase in pressure resulting from pumping during off peak hours (Giustolisi, et al., 2013). Therefore, considering water losses in addition to pumping energy cost is a good way of pump scheduling to minimize the total operational cost of the system.

A joint scheduling of pumps and pressure reducing valves is proposed by Shao, et al. (2019) to achieve both reduction of leakage and energy consumption. The research indicated that, after applying the solution to a small case study, it resulted in a 33.4% reduction of leakage and 25.4% reduction of energy consumption.

Harmonic oscillator tank is also recommended as another option to manage pressure (Latchoomun, et al., 2020). Optimal pumping and managing storage tank water level operation has showed a good result as a means of service pressure reduction to minimize leakage (Creaco, et al., 2016).

Some researchers also tried to make the operation of the water distribution system elements with real time and near real time control. For example, real time control of variable speed pumps is one suggested method (Page, et al., 2017). It proposes to control pressure by means of real time pressure measuring sensors and controllers which actuate the pumps based on the real time pressure measurements.

A study by Kang (2014) suggested an approach to improve real time optimal water control for reducing energy and non-revenue water. The research uses an approach of demand forecasting, hydraulic simulation using EPANET and optimization using genetic algorithm. The study was able to bring about optimal and near real time control settings. However, the simulation time was an issue in coming up with a real time solution.

Another study by Brentan, et al. (2017) proposes a real time puming operation by forecasting the demand every hour and updating the model with the new demand each time to determine PRV statuses and pumping speed which minimize energy and leakage . Their research further improved RTC to minimized computational time of simulation by using a data driven ANN model to simulate the physical hydraulic model. After being applied in a real WDS, the solution could result in 13% reduction in energy consumption.

In order to make the operation on real-time basis, the demand needs to be predicted beforehand in a short term manner of prediction like one day before the implementation. Researchers have been studying how short term water demand prediction models can be formulated and showed that the suggested models perform well. Several methods have been suggested so far including machine learning algorithms such as support vector machines, neural networks, k - nearest neighbors and some others.

The water demand of a water distribution network varies from one day to the other day although the demand patterns show similar shape. Peak demands are observed in the morning and evening while low demands appear during third quarter of the night. And the peak demand flow rate value differs each day as well as the time of occurrence of this peak which may lag or lead with minutes or few hours.

The variables considered for training the water demand prediction models are predominantly water demand history, weather (temperature and rain) and seasonality. By water demand history, it means that the water demand at time t of the next day is correlated to that of the current day and the previous few days. Regarding the other factors, such as temperature and rain, they affect the water consumption amount as they bring about behavioral changes on the users. It is noticeable that during hot weather, the water demand tends to increase significantly. In the same way, the occurrence of rainfall also alters the amount of water consumption considerably. Seasonality indicates periodically repeating trend of water demand. For instance, the water demand on weekends repeats itself weekly. Likewise, during major sport competitions such as world cup and during holydays such as Christmas a periodic similarity in pattern is observed in a long term manner (Trifunovic, 2020).

The machine learning methods of water demand forecasting have a very good accuracy despite the fact that they need enormous amount of historical dataset to establish the relationship between future water demand and the factors affecting it such as preceding demands and weather conditions. In contrast, traditional methods of forecasting such as Auto regressive integrated moving average (ARIMA) method predict with a lesser accuracy than the machine learning method but achieve satisfactory forecast while they do not demand as much historical data as ANN needs (Adebiyi, et al., 2014).

Short term water demand variation requires repeated prediction of loads and real time control of the system. Application of real time control (RTC) based on the expected demand is invaluable for efficient operation of water distribution systems. RTC is a control where the time gap between measurement and operational action is short relative to the response time of the system (Lobbrecht, 1997). In this case study, forecasted demand acts as the measurement, adjustment of pumping status as the action and total amount of leakage in the system corresponding to the expected demand as the response. The nodal pressures are determined by an EPANET Python library called WNTR.

Table 1 summarizes different leakage reduction mechanisms in water distribution networks proposed in the literatures.

Table 1 Literature Review Summary for Leakage Minimization Methods

Suggested Methods for Leakage Minimization				
No.	**Title of Paper**	**Methodology**	**Case Study**	**Description, Findings and Limitation**
1	Energy saving and leakage control in Water Distribution Networks: a joint research project between Italy and China (Berardi, et al., 2014)	DSS to design DMAs (District Metering Areas) Using WDNetXL		First Phase of the project. They have done optimal design of DMAs.And looking for further research to reduce energy and leakage.
2	Optimization of leakage and energy in the Abbiategrasso district (Creaco, et al., 2016)	Pressure Driven Approach and Well and Booster Pumps optimization to minimize Energy and Leakage	Milan, Italy	Districtualization, then optimization of well and booster pumps
3	Leakage Control in Water Distribution Networks by Using Optimal Pressure Management (Mahdavi, et al., 2011)	Optimal number and location of PRVs Using GA	Mahalat, Iran	Using Genetic Algorithm to determine optimal number of PRVs and their location
4	Embedding Linear Programming in multi objective genetic algorithms for reducing the size of search space with application to leakage minimization in WDNs (Creaco and Pezzinga, 2015)	Optimal location of control valves and identification of isolation valves to be closed	Santa Maria di Licodia, Italy	By hybridization of Linear programming and GA for control valve location optimization and isolation valve identification
5	Operational Optimization: Water Losses versus Energy Cost (Giustolisi, et al., 2013)	Optimal Pumping schedule	Not a Real world case study	Considering water losses in addition to pumping energy cost to come up with a pumping schedule which minimizes leakage and energy cost
6	Pressure control for minimizing leakage in water distribution systems (Samir, et al., 2017)	Using Effective setting of PRVs. Modelled with WATER CAD	Alexandrea, Egypt	PRVs in DMAs . A 37% drop in leakage was observed after the application of the solution.
7	Optimal Assets management of a water distribution network for leakage minimization based on an innovative index (Cavazzini, et al., 2020)	Minimizing LPI (Leakage Performance Index) and PRVs	Verona, Italy	Since leakage is not directly measurable, a Performance index is first formulated in terms of pressure and discharge. Then particle swarm optimization is used to find optimal setting of PRVs. And a 14.2% reduction in leakage was achieved.

8	Harmonic Oscillator tank: A new method of leakage and Energy Reduction in WDN with pressure driven demand (Latchoomun, et al., 2020)	Using tank water level for pressure management (Harmonic Oscillator Tank)	Not a Real world case study	Maintaining a range of water level and pressure in a tank to satisfy the the consumer needs while reducing leakage and Energy consumption
9	Leakage Control and Energy Consumption Optimization in the Water Distribution Network Based on Joint Scheduling of Pumps and Valves (Shao, et al., 2019)	Optimal Number and setting of PRVs and Optimal pump Scheduling	Not a Real world case study	Optimizing Operation of PRVs and Variable Speed Pumps using Genetic Algorithm. Resulted in a leakage reduction of 33.4% and Energy consumption reduction of 25.4%
10	Real-time optimal control of water distribution systems (Kang, 2014)	Pump Scheduling	Not a Real world case study	Demand forecasting, EPANET simulation and GA optimization
11	Near real time pump optimization and pressure management (Brentan, et al., 2017)	PRVs	Campos Do Conde, Brazil	Water Demand Forecasting is done every hour using adaptive Fourier series, meta modelling (ANN) is used to simulate the hydraulic model and Particle Swarm Optimization is done to find optimal pump status and PRVs
12	Pressure Management of Water Distribution Systems via the Remote Real-Time Control of Variable Speed Pumps (Page, et al., 2017)	Pressure Sensors and Controllers		Maintaining low pressure throughout the WDS by using Pressure Measurements from sensors to control speed of variable speed pumps.

Incorporating leakage in water distribution models by itself is an active topic of research. Most of the formulations to model leakage are based on the relationship between pressure and leakage flow. The emitter property of junctions in EPANET model enables to model leakage as orifices. And this needs calibration of emitter coefficient using pressure dependent analysis. Leakage modelling formulations suggested by some researchers is summarized in Table 2.

Table 2 Literature Review Summary for Leakage Modelling Formulations

Title of Paper	**Modelling Formulation**	**Methodology**	**Description**
Leakage Calibration of Water Distribution Networks (Maskit and Ostfeld, 2014)	$q_{leak} = \beta * l * P^{\alpha}$	Calibration of EPANET Model to find the values of α,β which model the leakage. Optimization using Genetic Algorithm and EPANET	Imaginary junctions were added in the middle of every pipe having the P-Leakage relationship mentioned to calculate leakage. Convergence is achieved while the demand and pressure at these junctions become close enough to the previous iteration.
Model Calibration and Leakage Assessment Applied to real WDN (Roma, et al., 2015)	$q_l(t) = Cp^{\gamma}$	Macro calibration (for demand) and Micro calibration (for leakage). Optimization using Genetic Algorithm to minimize RMSE	Leakage is modelled as an extra pressure dependant demand. $\gamma = 0.5$ is a constant of the model and the emitter coefficient C depends on the network and node
Modelling Leakage in WDS using EPANET (Gajbhiye, et al., 2017)	$q = c * h^N$	Using Emitter property of junctions on EPANET with Demand driven Approach. c=0.1 is used and EPANET was employed.	Leaking pipes identification was first made 10 nodes were selected as leaking points using two methods : Rule based (Older, smaller diameter and long pipes are assumed to be more prone to leakage) and Water Quality based (Low Cl residual indicates leakage)
Modelling Pressure: Leakage Response in Water Distribution Systems Considering Leak Area Variation (Kabaasha, et al., 2016)	$Q = k_1 * h^{0.5} + k_2 * h^{1.5}$	FAVAD (Fixed And Variable Area Discharges) $k1 = C_d * A_0 * (2g)^{0.5}$ $k2 = Cd * m * (2g)^{0.5}$ Global Gradient Algorithm (GGA) in EPANET	Leak area varies linearly with pressure. Incorporating leak area variation into hydraulic modelling is more rational. Hydraulically, leaks are orifices and therefore should adhere to the orifice equation together with their linear variation with pressure.
A new approach to model development of water distribution networks with high leakage and burst rates (Latchoomun, et al., 2015)	$BF - BF_{npd} = A. P^{N2}_{max}$	Based on Average zone Point (AZP) and Burst Frequency (BF)	based on leakage estimation from MNF and the burst frequency of AZP
Simultaneous Calibration of Leakages, Demands and Losses from Measurements. Application to the Guayaquil Network (Ecuador) (Martínez-Solano, et al., 2017)	Inflow = Demand + NRW	Matrix Solving iteratively	Leakage flow is a function of length of pipe and pressure along them. Three steps 1. Global Leakage coefficient calculation 2. Time Demand Pattern Calculation 3.Calibration by adjusting roughness and minor loss coefficients Three district metering Areas (DMA) are considered

There are two options for modeling the hydraulics of a water distribution system. The first method is known as demand-driven analysis (DDA), which assumes that nodal demand can always be supplied with sufficient pressure. The second method, pressure driven analysis (PDA), considers the reality that not all requested demand reaches to nodes. This method allocates water to nodes proportional to the available pressure at the nodes. Pressure driven analysis simulates water distribution networks with excessive leakage in a better accuracy than demand driven analysis.

Pressure driven analysis is more realistic but more complicated to model. It slows down the convergence of the steady state solver. There are different means of solving pressure driven models. The first one is by running the demand driven model iteratively. This method is easier but time consuming to run the model. The second one is through the application of demand driven models with added artificial elements like suitably chosen reservoirs until convergence is achieved. This method is effective and accurate but requires some preliminary adjustments. The other one is custom made pressure driven model majorly used by commercial tools (Mahmoud, et al., 2017).

Different researchers proposed equations to represent the pressure dependency of demand. In this research, since EPANET 2.2 is used for pressure driven analysis, the equation proposed by Wagner, et al. (1998) is applied which is expressed on *Equation 4*.

There are a number of algorithms to solve optimization problems. The basic method of finding optimal solutions is employed by using of derivatives or gradients of the objective function. But this method applies only when the objective functions can be expressed analytically. In cases where desired functions cannot be expressed analytically like the one in this research, direct and random search methods of algorithms are applied by means of computer programs. Among the global optimization (random search) algorithms, adaptive random search, adaptive covering cluster method and evolutionary (genetic) algorithms can be mentioned. Genetic algorithms are widely used optimization techniques which are also used in this research to find optimal pumping schedule in such a way that leakage and energy consumption by pumps would be minimal.

Pumping in WDN can be done either towards a storage tank which supplies the system by gravity or directly towards the network without storage tank. In the first case, the available head is always known, and the pump scheduling consists of ensuring that enough water is available at the tank at all times, with the minimal energy consumption. In the second case, two situations can be considered, one in which the variable speed pumps are used, case in which changes in the head and discharge can be made slowly. The second situation, which is considered in this research, is when traditional pumps with single speed are available. In this case, the operation is more challenging, as the conditions of the flow and pressure at the outlet of the pump changes according to the demand in the network, generating conditions that can be far from the ideal curve of pump operation and in consequence the performance of the pump is suboptimal. Besides, as the frequent on/off operation of the pumps generate surge transients with related pressure increments that are frequently generated, and that may produce damages in the system, including leaks. Another disadvantage of direct pumping towards the network is that a power failure may cause the depressurization of the system. For this reason, backup pumps with alternative energy source are common in these kinds of WDS.

In this research, optimization of pumping schedule in such conditions is studied as a solution to minimize leakage and energy consumed for pumping using real time control. The inclusion of pressure-driven demand analysis for real time control optimization of WDS which have direct pumping to the nodes was limited in the current studies, which is addressed in this research.

The case study area of this research is Braila, Romania water distribution network described in Chapter 2 .

1.2 Motivation

As the author of this research grew up in a society where many people face shortage of drinking water, to involve in a research which aims at saving water and energy loss means a lot. In the country where the author grew up the problem of water is mainly due to lack of water infrastructures and poor water management on areas where water infrastructure exist. Only 57 percent of the total population has access to safe drinking water (USAID, 2021). This makes the author to think that every drop of water counts. And it is really a pleasure for the writer to study optimization techniques for drinking water management.

1.3 Research Questions and Objectives

Main Objective

The objective of the research is to propose a framework for real-time optimal operation of pumps in water distribution systems so as to minimize the total volume of leakage as well as the pumping energy usage, under the constraints of network service and using a pressure driven analysis.

Specific Objectives

1) Formulate and solve an optimisation problem that involves pressure-driven demand analysis and RTC for pump scheduling
2) Develop a computational method to integrate RTC and model-based optimisation formulated in 1) for systems that pump directly to the network
3) Evaluate the effectiveness of the resulting pump schedules using the method developed in 2), comparing the results with the current operation practice

Research Questions

1. How can pressure-driven demand analysis be applied to a real time control of optimal pump scheduling to minimize leakage and energy consumption?
2. How can pumping pattern be adjusted using real time control to optimally minimize leakage while maintaining minimum pressure for systems that pump directly to the network?
3. How effective is using real time optimal pump schedules together with pressure driven analysis in minimizing the amount of leakage and energy consumption in a water distribution network that pump directly to the network?

1.4 Practical value

The city of Braila has concerns about water losses in its supply network. Although the city has a water loss strategy with the purpose of decreasing losses, this problem is still going on. And Leakage reduction is a priority. At the moment, average leakage amounts to 750 l/h/km and the aim is to reduce it by 50 l/h/km down to 700 l/h/km. The Water Utility Company and the community will benefit from saving of the excessive amount of Energy which is being wasted to treat and transport the water which is not eventually reaching to the customers. And also, as a long term solution; along with saving much water, it will keep infrastructures like roads and buildings intact by avoiding the damage of foundations underground due to leaked water.

Furthermore, minimizing leakage benefits the environment in two ways. The first is through conservation of fresh water. It helps to save water to meet the growing water demand due to population and economic growth. The second is through conservation of energy. Especially in areas where the energy source is fossil fuel, reducing the energy results in less air pollution and hence less damage on the environment.

Chapter 2 Case Study Area

2.1 NAIADES Project

NAIADES an European Commission project aiming at the digitization of the water sector by transforming water management actions into optimized, sustainable and eco-friendly solutions through state of the art ICT – based smart water management systems (NAIADES-Project, 2021). The project consists of three use case areas one of which is Braila, Romania water distribution network which is considered in this research.

2.2 Generalities about the Area

Braila is a city in Muntenia, Eastern Romania and a port on Danube River. Based on the 2011 Romanian census, there were 180,302 people living in the city (Population.City, 2015). The city has a flat topography. The source of water for the city is the Danube River. And the city has a problem of water losses on its water distribution network. Currently; the estimated amount of leakage on Braila's water distribution system is on average 750 l/h/km.

The Utility Company of the city has been using the Supervisory Control and Data Acquisition (SCADA) system to manage the operation of the water distribution network, although operation is not assisted by a Real Time Control System. And the management practice was not sufficiently supported by modelling tools. But, recently the company acquired a WDN model which can be used to assist the operational management of the system. Figure 1 shows the map of Braila City.

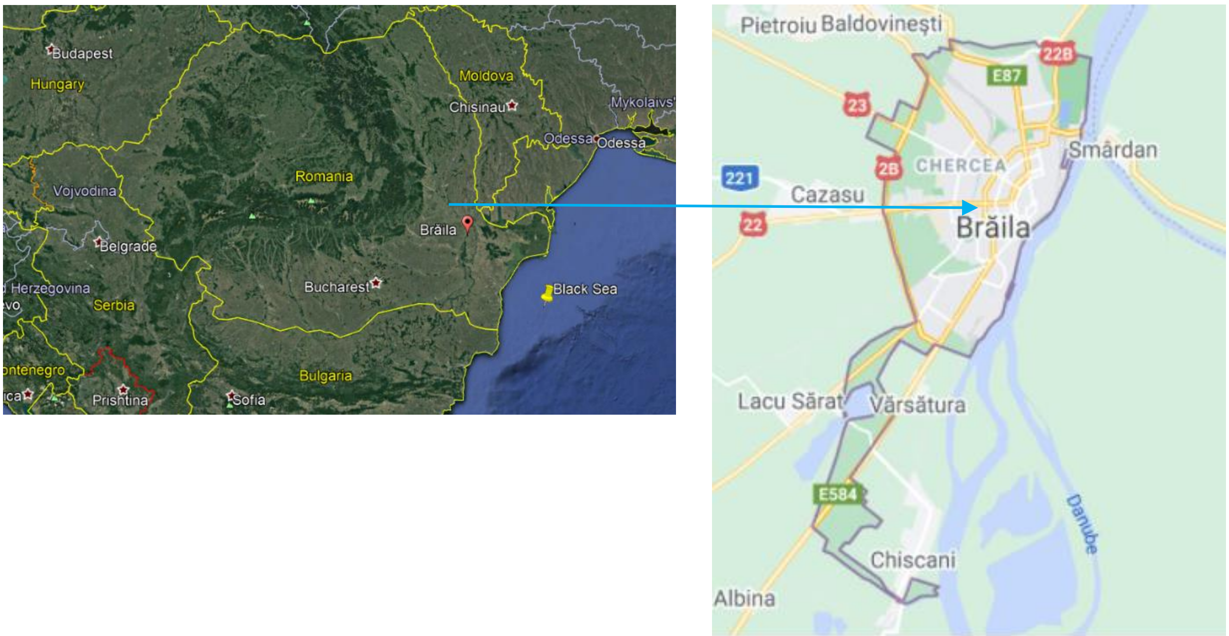


Figure 1 Map of Braila, Romania

2.3 Water Supply System of Braila Water Distribution Network

The general information described on sections 2.3.1 to 2.3.4 is taken from the hydraulic modelling report of (S.C Company of Public Utilities Dunaria Braila SA, 2019).

2.3.1 Source of Water

Water catchment is done from a surface water source - the Danube River, in the area of Chiscani locality. It has the capacity to provide water for all the localities situated in the north of the county. The raw water collected through the bank intake is sent to the Chiscani treatment plant, where it is treated and transported in the 3 storage complexes: Radu Negru, Apollo and Brăila.

The catchment from Chiscani, with permanent operation (365 days/year, 24 hours/day), has an installed capacity Q = 1,000 l/s and was put into operation in 2000. The bank outlet is located on the adduction canal of SC Thermoelectric S.A. - Brăila branch and it is at CT = 4 m.

2.3.2 Storage Reservoirs

The storage of the necessary water for the consumers of the Municipality of Brăila is located in the three water households, through 4 tanks, with a total capacity of 65,000 m3, described as follows:

Radu Negru water house – has a total storage capacity of 20,000 m3: 1 x 20,000 m3 semi-buried tank, made of monolithic reinforced concrete. From here, the water is pumped into the distribution network, ensuring the necessary flow to the consumers on the south of the city as well as supplying the Apollo complex.

Apollo water house – has a total storage capacity of 40,000 m3: 2 x 20,000 m3 semi-buried tanks, made of monolithic reinforced concrete. From here, the water is pumped into the distribution network, ensuring the necessary flow to consumers on the north of the city.

Brăila water house (located within the Braila treatment plant) – has a total storage capacity of 5,000 m3: 1 x 5,000 m3 tank made of monolithic reinforced concrete.

2.3.3 Pumps and Pumping Stations

The water distribution towards the consumers is achieved by pumping. At the Braila ATU level there are three water pumping stations in the distribution network, with the following characteristics:

Radu Negru pumping station: pumps drinking water into the city's distribution network, ensuring the necessary flow to the consumers from the south of Brăila, and to the Apollo storage complex.

Braila pumping station pumps drinking water into the city's distribution network. It is equipped with 2 + 1 electric pumps with Qp = 850 m3/h and Hp = 35 m.

The Apollo pumping station pumps drinking water into the city's distribution network, ensuring the necessary flow to the consumers in the north of Braila. It is equipped with 2 + 1 electric pumps with Qp = 1100 m3/h and Hp = 25 m.

Figure 2 shows the locations of storage reservoirs in Braila.

Figure 2 Locations of Storage Tanks in Braila Water Distribution System

Figure 3 shows the summary chart of water transport from the Danube River to areas in Braila city through pumping intermediate storage tanks.

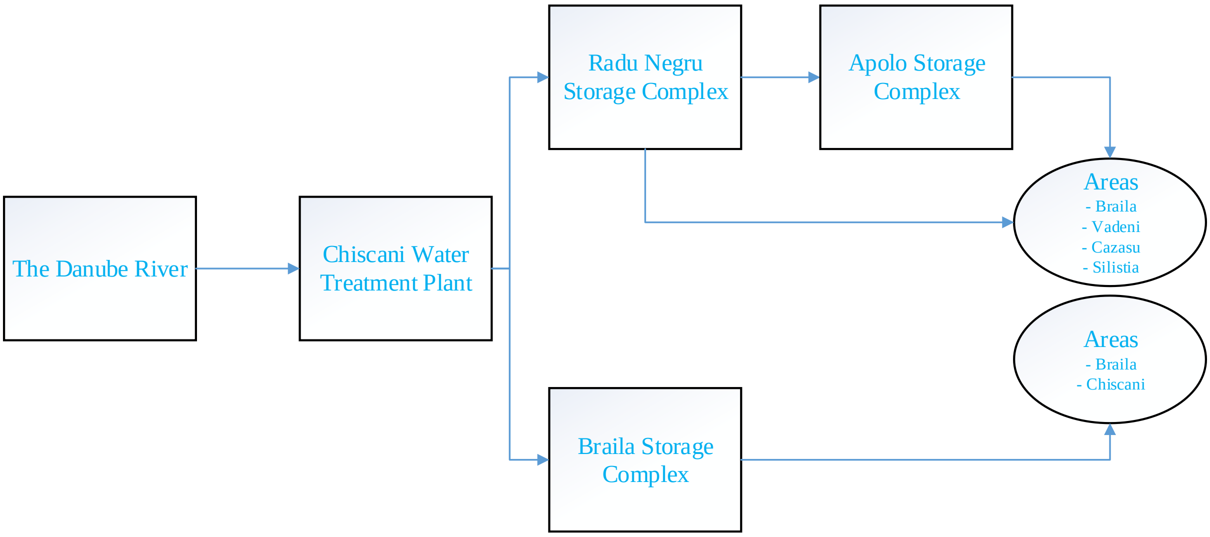


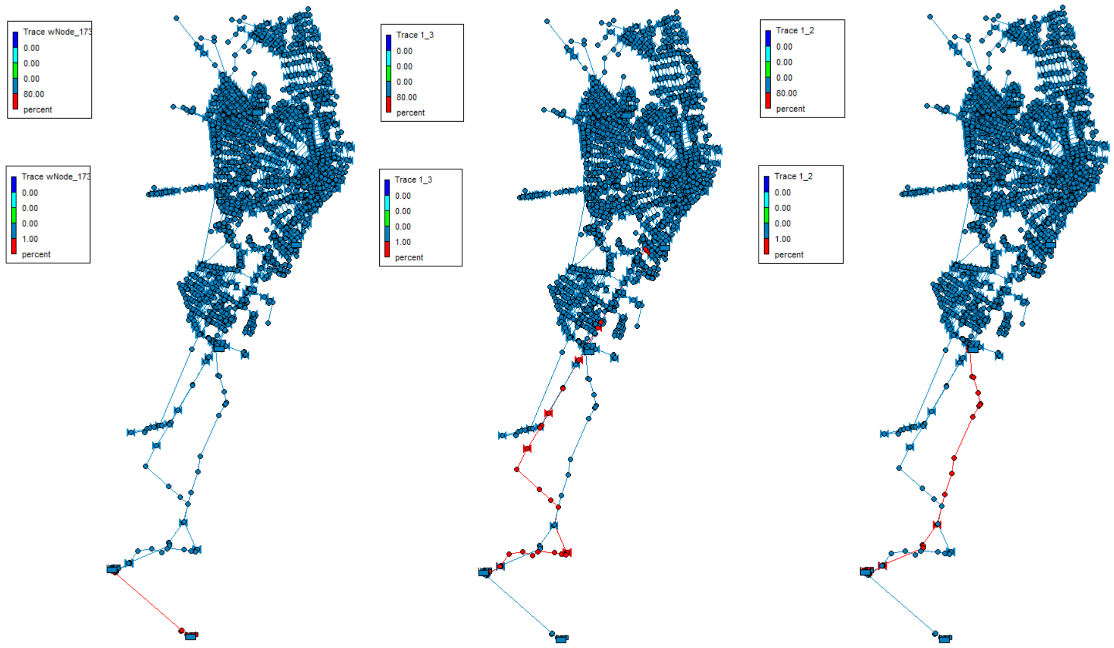
Figure 3 Water Transport Summary Chart of Braila WDS

The list of pumps and their destination is listed on Table 3.

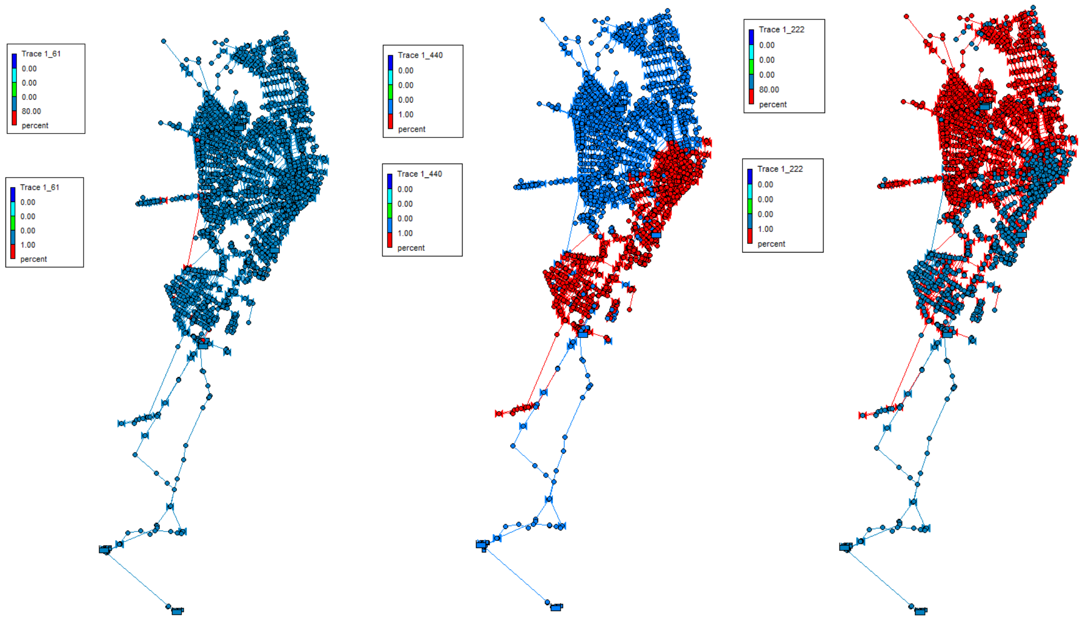
Table 3 Transport System and List of Pumps in Braila WDS

Pump Name on EPANET model	**Transports From Location**	**To Location**	**Length of Pipe (Km)**	**Pipe Nominal Diameter (mm)**
wLink_5794	Danube River	Chiscani Treatment Plant	2.7	1200
wLink_5825	Chiscani Treatment Plant	Radu Negru Storage Complex	7.8	1000
wLink_5796	Chiscani Treatment Plant	Braila Storage Complex	12	800
wLink_5800	Radu Negru Storage Complex	Apollo Storage Complex	7.8	630
wLink_5805	Braila Storage Complex	To the Pipe Network		
wLink_5806	Apollo Storage Complex	To the Pipe Network		

Figure 4 shows graphically which pumps supply which area of the network and storage tanks. The nodes and pipes marked in red show water coverage from tracing result of the EPANET model.



a) Danube to Chiscani TP b) Chiscani to Braila storage c) Chiscani to RaduNegru Storage



d) Radu Negru to Apollo e) Braila Storage to the Network f) Apollo storage to the network

Figure 4 Pumps Supplying Storage tanks and directly to Nodes

Figure 5 depicts the water transport (marked in blue) from the Danube River to Braila and the nearby areas.

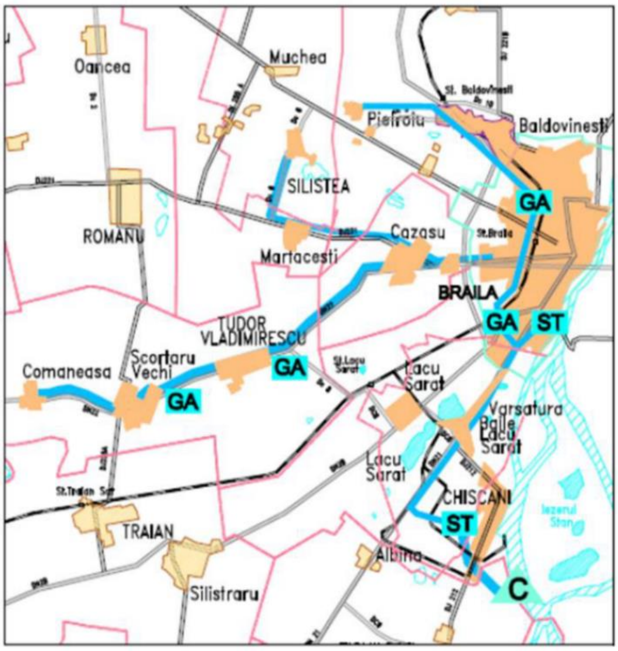


Figure 5 Water transport from the Danube River to Braila WDS and nearby areas

Degree of Connection

Currently, the degree of connection to the distribution network is 98.72% and is achieved through 26,059 connections, out of which:

- Domestic subscribers' connections: 22,914 pcs.
- Associations of owners' connections: 1,129 pcs.
- Economic agents' connections: 1,553 pcs.
- Public institutions' connections: 448 pcs.
- Domestic consumption connections: 15 pcs.

The water consumption is 100% metered, at catchment and distribution, and 94.17% at the users' connections.

2.3.4 District Metering Areas (DMAs)

There are many advantages of creating DMAs in a water distribution system since it makes the management easier as the network area gets smaller. And it becomes easier for active loss control. Moreover, losses can quickly be identified with daily consumption monitoring.

The Braila WDS is subdivided in to 20 District Metering Areas (DMAs). There are 8 existing and 12 projected DMAs as shown in Figure 6.

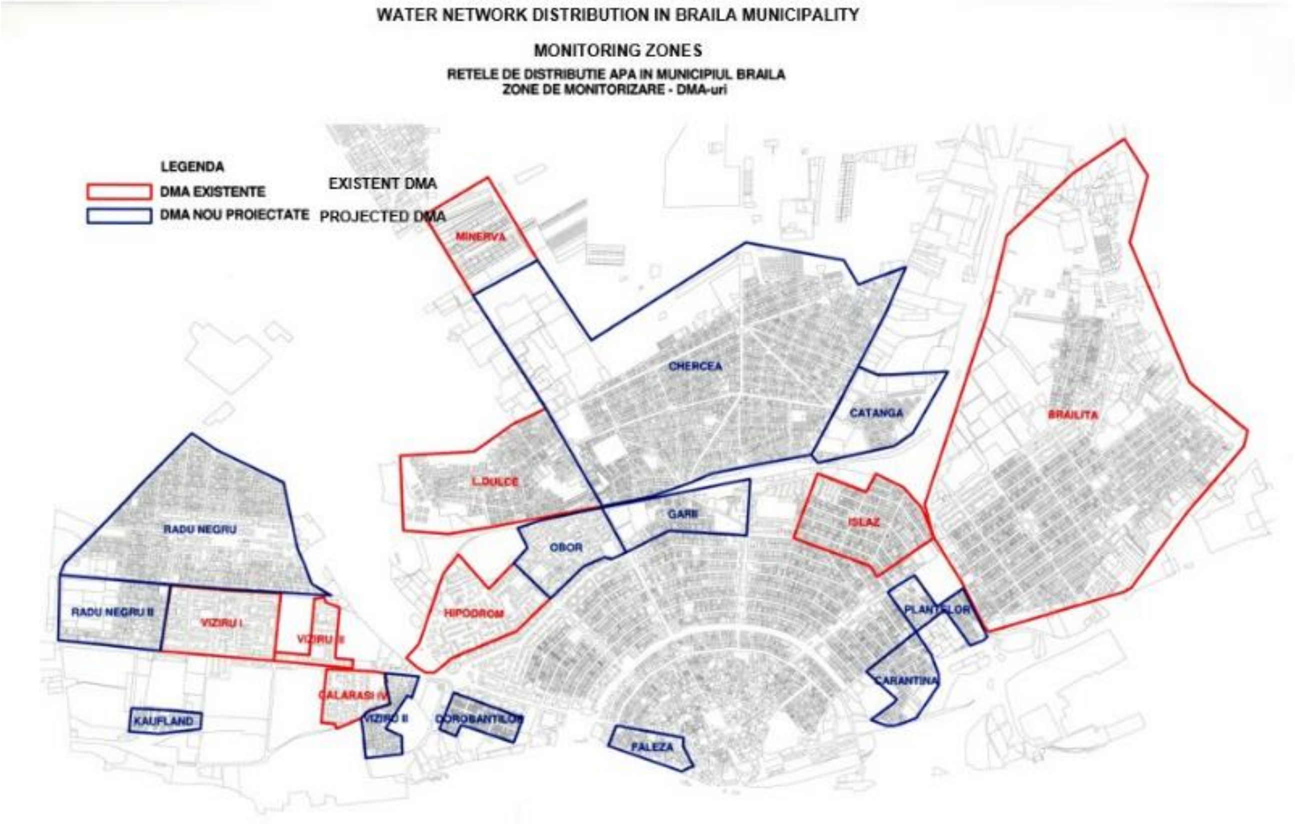


Figure 6 District Metering Areas of Braila WDS

2.4 Available Data

The data available were the following:

- GIS Data including user locations, consumption data per customer, location of pumps and valves and traffic map of the city
- Operational description of the system by local operators (Word Document)
- Map of the system showing the existing and projected District Metering Areas
- EPANET Hydraulic Model of the water distribution Network
- Hydraulic Model Report (written in Romanian language)

2.5 Available Hydraulic Model

The water distribution model of the city is developed using a demand-driven analysis by EPANET modelling software. The system consists of 4172 Junctions, 6 Reservoirs, 3184 Pipes, 1505 Valves, 6 main Pumps and 8 standby pumps. Leakage was not separately considered in the modelling process. Therefore, now, it is incorporated to the model considering it as a pressure dependent variable.

2.5.1 Demand pattern

The daily average consumption used in the Braila WDN model is 294 lps. The demand pattern of the model is presented in Figure 7.

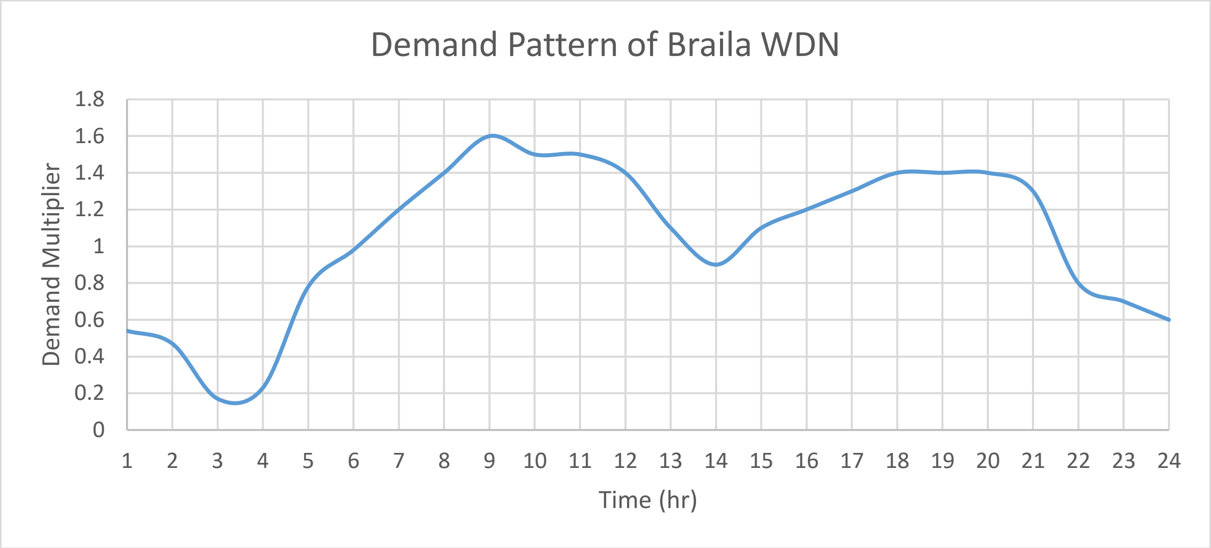
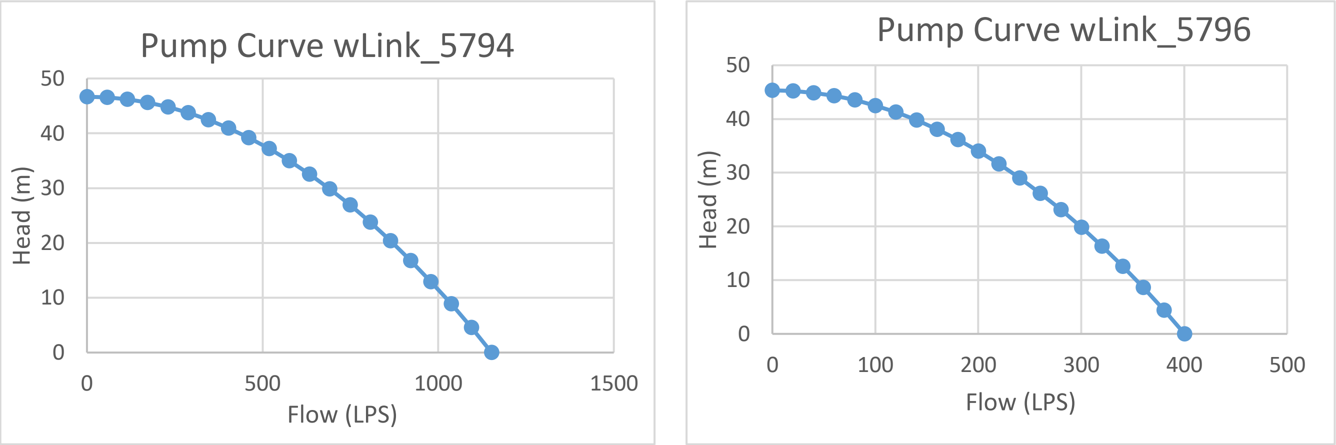


Figure 7 Demand Pattern of the Braila WDN Model

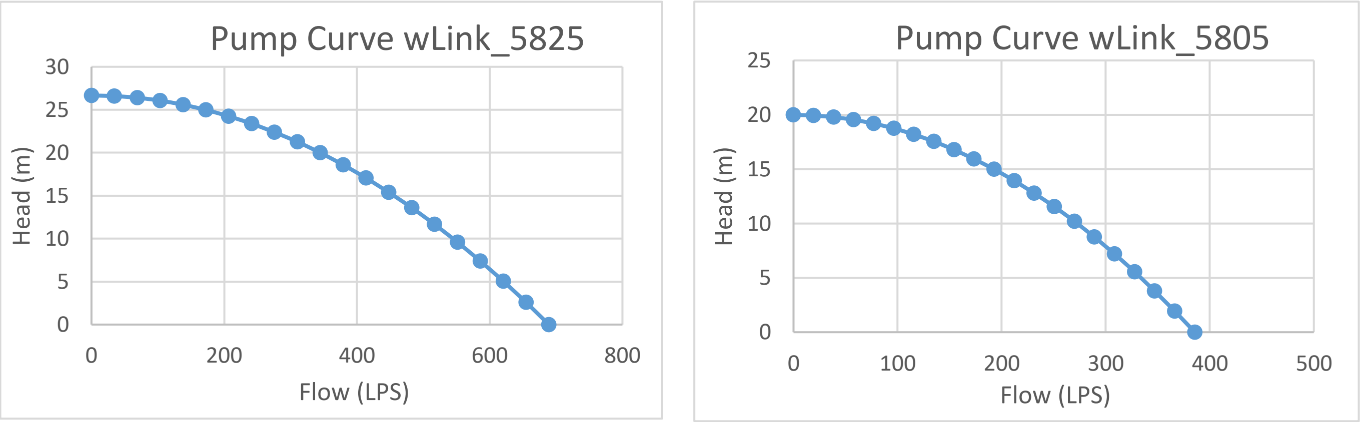
2.5.2 Pump Curves

The pump curves of the main pumps in Braila WDN are shown with Figure 8) a to Figure 8*) f*.

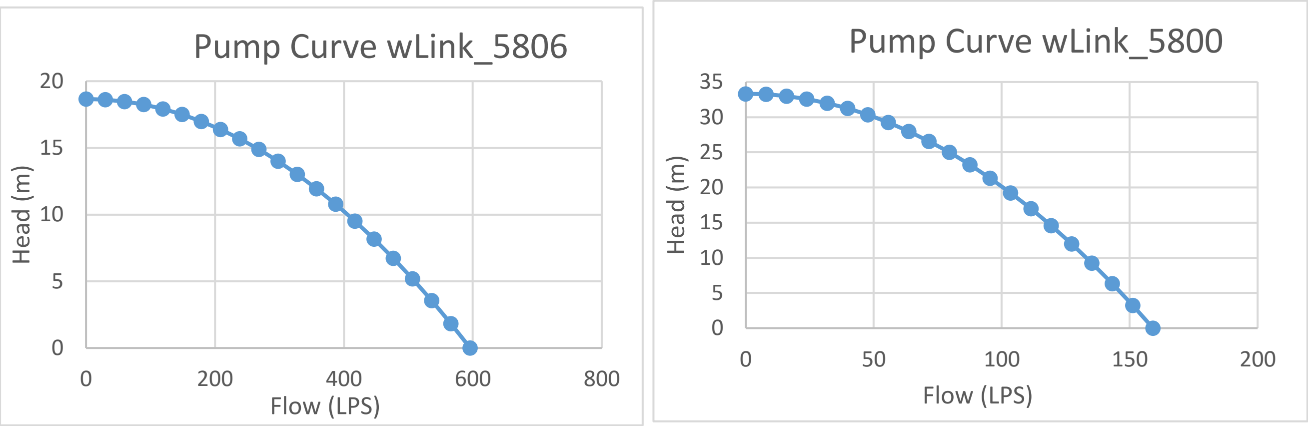


a) Curve of Pump (Danube to Chiscani)

d) Curve of Pump (Chiscani to Braila)



b) Curve of Pump (Chiscani to Radu Negru) e) Curve of Pump (Braila to the Network)



c) Curve of Pump (Apollo to the Network) f) Curve of pump (Radu Negru to Apollo)

Figure 8 Braila WDN Main Pump Curves

Chapter 3 Methodology and Tools

3.1 General Outline

The approach which is used to solve the problem of leakage in this study is by pressure management through optimal RTC operations. The higher the pressure in the system elements, the larger the leakage volume. Thus, reducing the pressure in the system elements would be a good way to minimize the leakage. But minimizing the pressure below a certain limit causes the system to be unable to satisfy the demand at nodes. Therefore, for critical nodes, minimum pressure is set first as a constraint. And, then, water demand forecasting method is adopted to predict the water demand on each next day. Finally, the optimization algorithm is run taking the predicted demand and previous day pumping schedule as an input to come up with an operation which minimizes both leakage and energy consumed by pumps. Therefore, it will be possible to avoid excessive leakage and energy consumption by anticipating the demand beforehand and managing the operation of pumps optimally to meet the objectives, which makes the operation real time control.

In terms of tools, EPANET software is used for modelling the water distribution network and a Python script is written using “WNTR” Python library which is used to run the model, manipulate the input data and report the results. The Genetic Algorithm Optimization solver Platypus, a Python library is adopted to solve the model based optimization problem.

3.2 Procedure

Figure 9 displays the overall procedure of the research.

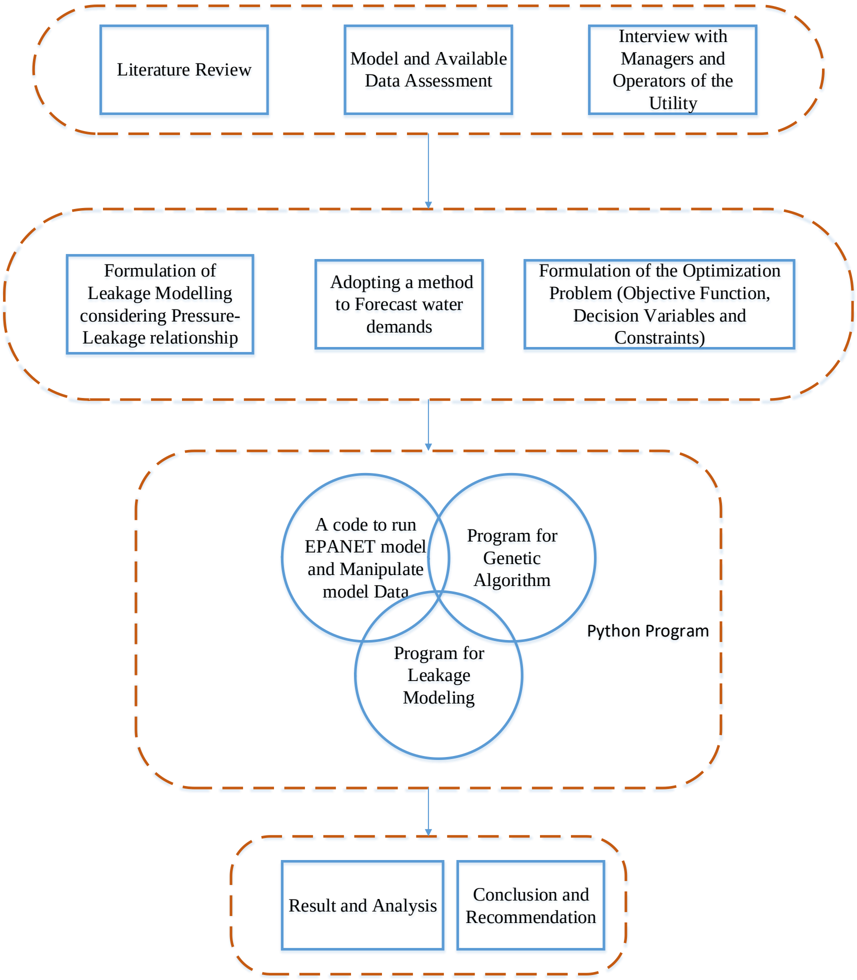


Figure 9 Research flow chart

3.3 Tools

During this research majorly three tools were employed, namely: EPANET hydraulic modelling tool, Python programming language and QGIS geographic information systems software. In addition, special Python libraries such as WNTR and Platypus packages were applied throughout the research together with other Python libraries such as NumPy, Pandas, Matplotlib and Seaborn.

3.3.1 EPANET modelling tool

EPANET is a hydraulic modeling software aiming at simulation and analysis of hydraulic and water quality in pipe networks. It enables to track the flow of water in each pipe, the pressure at each node, the height of water in each tank, and the concentration of a chemical species throughout the network (Rossman, et al., 2020).

The tool takes as an input the physical and non-physical network elements. Then, it solves friction head loss and continuity equations to compute flow in each pipe and pressure at each node at each time step of the simulation. Head loss in pipes is computed using one of Hazen-Williams, Darcy-Weisbach, or Chezy-Manning formulas.

It is possible to view the results of the simulation run in a various ways. These include color-coded network maps, data tables, time series graphs, and contour plots (Rossman, et al., 2020).

EPANET models a water distribution system as a collection of links connected to nodes (Rossman, et al., 2020). The term node includes demand junctions, tanks, reservoirs (sources or sinks). And elements considered as links are valves, pipes and pumps. The following definition of EPANET network elements listed on Table 4 EPANET network elements with their definitions are extracted from the EPANET 2.2 manual (Rossman, et al., 2020).

Table 4 EPANET network elements with their definitions

EPANET Element	Definition
Junctions	Nodes on which inflow or outflow of water to and from the network is assigned
Reservoirs	Nodes that represent infinite external source or sink of water to the network
Tanks	Storages with defined storage capacity where stored water volume can vary with time
Emitters	Devices used to represent flow through a nozzle or an orifice
Pipes	Links that convey water between nodes in the network
Pumps	Links that raise the hydraulic head by imparting energy to the water
Valves	Links that limit flow or pressure at a certain point of the network
Non-Physical Components	Curves (such as pump curve), Time patterns (to vary quantities over time) and Controls (Statement to determine how the network is operated)

3.3.2 WNTR Python Module

WNTR (Water Network Tool for Resilience) is a Python module developed to model and analyze water distribution networks. With this package, it is possible to generate new network from scratch, modify the model elements, modify operation of elements such as pumps, add disruptive events such as pipe leaks and power outages, and add response strategies, run hydraulic and water quality simulation, compute resilience metrics, run probabilistic simulations as well as analyze results and generate graphics (Klise, et al., 2018).

It is possible to combine this module with other Python modules such as NumPy, SciPy, Pandas, and so on. In this research, the WNTR module is used to modify the considered water distribution model demand and pumping patterns, as well as for running pressure driven hydraulic analysis, leakage modelling, generating total leakage and energy consumption results. And in combination with Platypus Python package, multi objective optimization of pumping operation schedule was done based on the leakage and energy as well as pressure results of WNTR analysis.

WNTR has two hydraulic simulation options called WNTRSimulator and EPANETSimulator each one having its own advantages and disadvantages with the available current version of WNTR module. WNTRSimulator has the capability of water quality modelling and leakage modelling, in addition to the hydraulic modeling. Whereas, the EPANETSimulator does not have these two capabilities. On the other hand, the WNTRSimulator lacks the capability for pattern modification which is possible with only the EPANETSimulator. In this research, pattern modification and leakage modelling are vital elements that are needed to iteratively test different pumping patterns and check the resulting leakage. But, it is not possible to get both of these tools in one of the simulators. Therefore, the EPANETSimulator is selected and its disadvantage which is inability to model leaks is supported by writing a new python function which calculates leakage rate based on the available pressure using the emitter property of junctions.

3.3.3 Platypus Python Module

Platypus is a library for evolutionary computing in Python developed aiming at solving multi-objective optimization problems using evolutionary algorithms (MOEAs). Unlike other available optimization libraries platypus provides algorithms and analysis tools for multi-objective optimization.

3.3.4 QGIS

QGIS is a free and open access geographic information system tool. In this research, it was used to analyze interaction between the water distribution network and Traffic Roads in the city. There are plugins to import and export EPANET input files to the QGIS platform to analyze and edit spatial information. With this tool, it was managed to determine pipes overlaid by major traffic roads extracted from open street map. This in turn helped to determine potential leaking pipes.

3.4 Hydraulic Analysis

The hydraulic calculation by the EPANET software is based on solving for hydraulic variables satisfying the conservation of mass and conservation of energy. These two laws are written as equation of continuity and head loss equations which form a matrix of equations. The tool solves these matrix to determine the hydraulic state of pipe network at a given time and point using iterative solving mechanism of gradient method which was originally suggested by Todini (Rossman, et al., 2020).

The first set of equations is with respect to the law of conservation of energy. Based on the conservation of energy, the total energy (summation of pressure head, potential head and kinetic head) between two nodes should be kept constant.

$$P_1 + \frac{V_1^2}{2g} + Z_1 + h_p = P_2 + \frac{V_2^2}{2g} + Z_2 + h_L \qquad \textit{Equation 1}$$

Where: Subscripts 1 and 2: Node one and Node 2 connected with a pipe

P = *Pressure Head*

V = *Velocity*

Z = *Elevation*

h_p = *Pump head*

h_L =*Friction and local head losses between the two nodes*

At nodes, only elevation head and pressure head exist. Therefore, ignoring the first two terms of the equation from both sides, the equation will reduce to the form of the head loss equation given by:

$$H_i - H_j = rQ_{ij}^n + mQ_{ij}^2 \qquad \textit{Equation 2}$$

Where: i and j refer to the two connected nodes

H = *nodal head*

h_{ij} = *head loss between nodes i and j*

Q_{ij} = *flow rate between nodes i and j*

r = resistance coefficient

m = minor loss coefficient

n = major loss coefficient (1.85 for Hazen Williams head loss equation and 2 for Darcy Weisbach)

For each pipe in the network connecting two nodes, *Equation 2* will be written so that conservation of energy would be satisfied.

The second set of equations is regarding the conservation of mass which leaves us with the continuity equation that says the sum of the total mass of water entering and leaving a node should be zero. And if the node is a storage tank or reservoir, the sum of inflow rate and out flow rate should balance the storage volume change with time. Continuity equation is to be calculated at each node and it is expressed as written in *Equation 3*:

$$\sum_j Q_{ij} - D_j = 0 \qquad \textit{Equation 3}$$

Where: Di = *Demand at a node*

Q_{ij} = *flow rate to or from the considered node (flow into a node is positive by convention)*

Equation 3 is written for each node in the network so as to satisfy the conservation of mass.

The matrix formed by the two sets of equations will have a number of unknowns less than number of equations which makes it solvable. And finally after multiple iteration runs to solve the matrix, when convergence is met, the flow and velocity in each pipe and pressure and head at each node in the network are determined for each time of the simulation.

3.4.1 Demand Driven Analysis (DDA)

Demand Driven Analysis assumes that any demand requested at each node can be supplied with sufficient pressure. But, in reality this may not always happen. There can be nodes where there is not enough pressure to supply the requested amount of demand due to reasons such as pump failure, pipe burst and excessive demand. To address this issue, another method of analysis should be employed which enables to simulate the reality by allocating demand amount proportional to the available pressure. And this method is called pressure driven analysis which is more realistic and more complicated to model as discussed in section 3.4.2.

3.4.2 Pressure Driven Analysis (PDA)

The pressure driven analysis is developed considering the fact that demand depends on pressure head available at nodes. Water demands are classified as consumption and leakage where both kinds of demands are dependent on the available pressure at the node. Leakage demands are modelled separately as orifice flow which is also pressure-dependent flow. In this section, pressure driven analysis is discussed for the consumption water demands only. And the leakage demand relationship with pressure is discussed in section 3.6.1.

Figure 10 describes the water demand classification in water distribution networks.

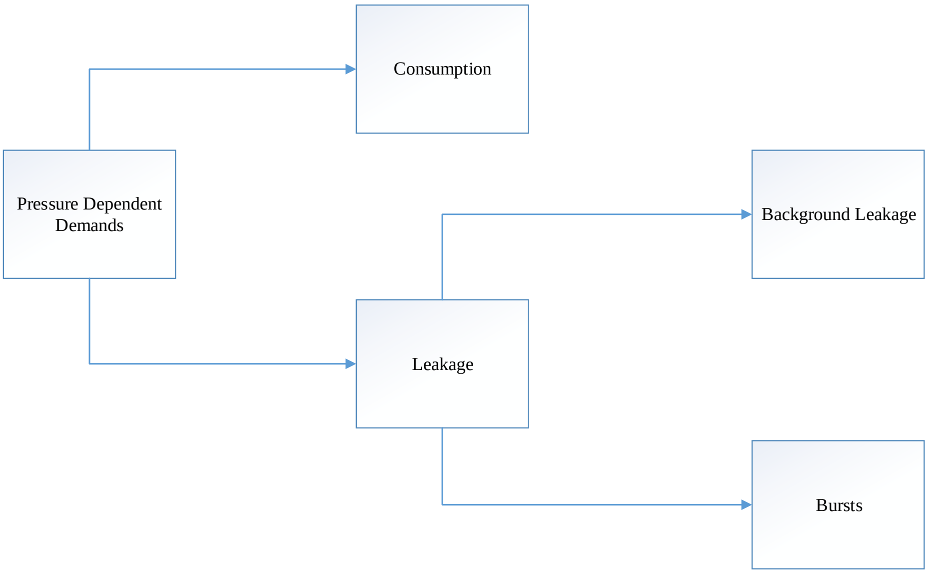


Figure 10 Demand classification Flowchart

PDA works as follows. When the pressure required to supply the whole amount of demand is available at a node, then all the requested amount of flow will be provided. Otherwise, when there is a lower pressure than the required one, then an amount of demand proportional to the average pressure will be supplied. And when the pressure at the node is below the minimum pressure possible, no demand is supplied to that node.

There are several demand pressure relationships proposed by researchers. EPANET 2.2 which is used in this study applies the demand-pressure relationship proposed by Wagner, et al. (1998) as expressed on Equation 4.

$$d = \begin{cases} 0 & if \;\; p < p0 \\ D_f \frac{p-p0}{pf-p0} & if \;\; p0 < p < pf \\ D_f & if \; p > pf \end{cases} \qquad \text{Equation 4}$$

Where: d = Actual Demand

Df = Desired Demand

P = Available Pressure

P0 = Minimum Pressure

Pf = Required Pressure

Minimum Pressure is the pressure where the nodes with pressure below this amount will not get any flow. Whereas the required pressure is the pressure required to supply the full demanded flow. And if a pressure at a node is below the required pressure but above the minimum pressure, it gets a flow of lesser amount than the requested based on the proportion shown in Equation 4.

Figure 11 shows how actual demand varies with the available pressure. The figure is taken from (Wagner, et al., 1998).

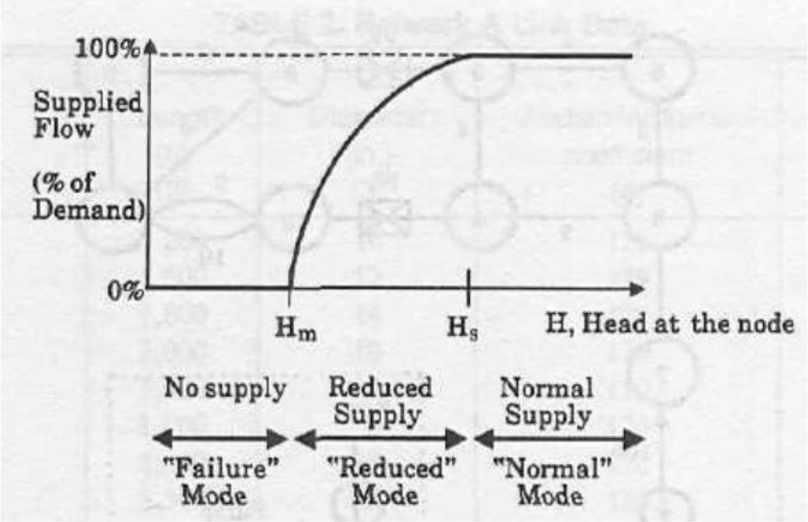


Figure 11 Pressure - Demand Relationship

3.5 Formulation of the Optimization Problem

Optimization is the process of finding the values of a set of decision variables, which either minimize or maximize one or more objective functions while satisfying specific constraints. When the number of desired objective functions to be optimized are more than one, the optimization process is called multi-objective optimization. The objective functions are usually conflicting. In water management, optimization is widely used to solve problems in the fields such as reservoir operation to maximize total gain from power production, irrigation and navigability; water allocation to different users like public water supply and irrigation; optimization of pipe sizes minimizing flood damage and material cost in urban drainage networks; model calibration to search for values of parameters which result in minimum difference between model and reality (Solomatine, 2020). It is also for finding optimal pumping schedules in water distribution networks to minimize energy consumption and leakage volume while satisfying service pressure requirements which is the task of this research.

3.5.1 Objective functions (Leakage and Energy)

The optimization will be directed towards minimization of total volume of leakage lost through assumed leaking nodes in the network and the total energy consumed by pumps in the water distribution network.

The formulation of the optimization problem is:

$$ObF1 = Min(L)$$

$$ObF2 = Min(E)$$

$$\mathrm{L} = \mathrm{f}(D, \mathrm{P1}_{\mathrm{status}}, \mathrm{P2}_{\mathrm{status}}, \mathrm{P3}_{\mathrm{status}}, \ldots\ \mathrm{Pn}_{\mathrm{status}})_{\mathrm{t}} \quad \text{for t} = 0,1,.\ .\ .,24\ hr$$

$$\mathrm{E} = \mathrm{f}(D, \mathrm{P1}_{\mathrm{status}}, \mathrm{P2}_{\mathrm{status}}, \mathrm{P3}_{\mathrm{status}}, \ldots\ \mathrm{Pn}_{\mathrm{status}})_{\mathrm{t}} \quad \text{for t} = 0,1,.\ .\ .,24\ hr$$

$$P_{\ i\ status} = (on, off)$$

Where, L= Total volume of leaked water in the network

E = Total Energy used by pumps per day

D = Demand at nodes

$P_{i\ status}$ = *operational status of pump i at time step t*

n = Number of Pumps in the network

OBF = Objective Function

The first objective function is minimizing leakage which is a function of available pressure at each node. Leakage modelling is done using an emitter, EPANET junction property, by means of assigning emitter coefficient and emitter exponent parameters at the selected leaking nodes in the network.

The relationship between leakage flow rate and available pressure in a junction is represented by the orifice flow equation shown as *Equation 5*:

$$q = Cp^{\gamma}$$

Equation 5 Orifice Discharge Equation

Where: q = flow rate

P = Pressure

C = Discharge Coefficient

Υ *= Emitter exponent*

Leakage volume is then calculated by multiplying the leakage rate with simulation time which is usually 24 hrs. And the total volume becomes the sum for all leaking nodes.

$$V_{leak} = \sum_{i=1}^{n} q_{leak,i} * t_{sim}$$

Equation 6 Leakage Volume

Where: V_{leak} = *Leakage Volume in the Network (m^3)*

q_{leak} = *Leakage Rate at the leaking node (m^3/s)*

t_{sim} = *Simulation time (seconds)*

The second objective function is minimizing Energy consumed by pumps. Energy usage is calculated using *Equation 7,*

$$E = \frac{\Upsilon * Q * H}{\eta} * Tsim$$

Equation 7

Where: E = Energy Consumed (kWh)

Q = Flow rate (m3/s)

H = Head (m)

η *= Efficiency of the pump (Usually about 75%)*

Υ *= Unit Weight of water (9.81 KN/m3)*

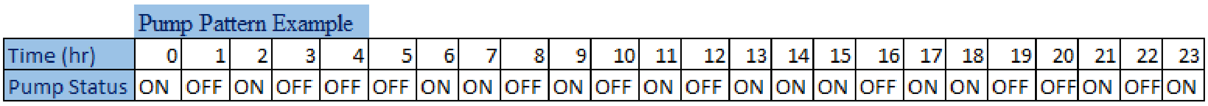
Tsim = Total simulation time (hr)

Energy Consumed can directly be read from the EPANET or using a python command with WNTR module.

3.5.2 Decision variables

The decision variables of the optimization problem are pump statuses at different times of the day which have binary value. Values of 1's and 0's represent on and off condition of a pump respectively during the considered hour of the day. The list of these values for each time of the simulation time makes the pumping pattern of the considered pump. Assuming a time step of 1 hour, a pump will have 24 values (decision variables) for one day simulation time. *Table 5* is an example pumping pattern for one pump with time step of one hour and twenty-four hours simulation time.

Table 5 Example Decision Variables considering a single pump



Pump Pattern Example

Time (hr)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Pump Status	ON	OFF	ON	OFF	OFF	OFF	ON	ON	OFF	ON	OFF	ON	OFF	ON	ON	ON	OFF	ON	ON	OFF	OFF	ON	OFF	ON

The optimization algorithm tries to find list of pumping patterns which minimize total leakage volume and energy usage by pumps.

3.5.3 Constraints

The constraint is minimum service pressure which should be maintained to satisfy the demand at critical nodes. Critical nodes are those nodes which have high possibility of experiencing a large amount of drop in pressure making it impossible to meet the demand.

$$P_{Critical\ nodes} \geq Minimum\ Pressure$$

The selection of these critical nodes is based on the pressure values resulting from demand driven analysis of the model. Those nodes which have minimal pressure values are prone to become unable to meet the minimum service pressure. Therefore, maintaining the service pressure at these critical nodes will be considered as a constraint in the optimization process. Figure 12 shows the pressure map result of the model after a demand driven analysis run.

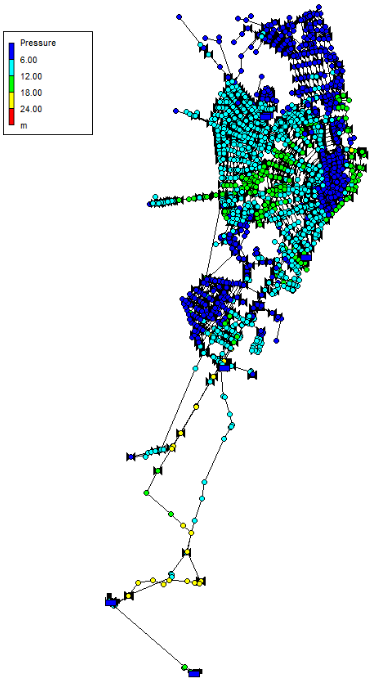


Figure 12 Pressure Map Result of Demand Driven Run of the Model

Using Queries tool of the EPANET software critical nodes were selected based on their pressure at 08:00 O'clock which is also a critical time, then, 16 nodes were found out to have less than 2.3m pressure value which are presented in Table 6.

Table 6 Critical Nodes with Pressure below 2.3m

DESCRIPTION		
Network Table - Nodes at 8:00 Hrs		
Critical Nodes (P < 2.3m at 08:00hr)	**Demand**	**Pressure**
Node ID	LPS	m
Junc 1_20	0.55	2.01
Junc wNode_2978	0.08	2.25
Junc wNode_2983	0.03	2.27
Junc wNode_2984	0.05	2.25
Junc wNode_3009	0.19	1.13
Junc wNode_3082	0.24	2.27
Junc wNode_3146	0.07	2.25
Junc wNode_4630	0.1	2.01
Junc wNode_4636	0	2.05
Junc wNode_4647	0.03	2.05
Junc wNode_4675	0.03	2.04
Junc wNode_4678	0.01	2.04
Junc wNode_4680	0.01	2.07
Junc wNode_5041	0.14	2.07
Junc wNode_832	0.01	2.09
Junc wNode_891	0.01	2.22

3.5.4 Search Space Analysis

In this research, the decision variables are pump scheduling patterns (on/off values of pumps) at different hours of the day. Assuming a time step of 1hr, one pump will have 24 variables which can have values of 0 or 1 representing on/off status during each hour of the day. Considering three pumps to optimize, there will be 72 decision variables representing each hourly status of the three pumps during the 24 hrs. Each 72 decision variables can take binary values of 0 or 1, which leaves us with $2^{72} = 4.72 \times 10^{21}$ possible combinations. It is impossible to run the EPANET simulation and test the result for all possible combinations and select the ones resulting in minimum leakage and energy consumption. Random search methods such as genetic algorithm help tackle this issue as they make ways of screening to ignore large set of bad points and let best points remain. Genetic algorithm is one type of random search methods to test only selected points which have higher potential of being the optimal solution. Table 4 shows the number of possible patterns considering different number of pumps.

Values Per Decision Variable	2	(0/1)
time step	1	hr

$$Number\ of\ Possible\ Combinations = 2^{Total\ no.\ of\ Decision\ variables}$$

Table 7 Combinatorial for different number of pumps

Number of Pumps to be Optimized	No. of Decision Variables per pump	Total Decision Variables	Possible Combinations
1	24	24	16777216
2	24	48	2.81475E+14
3	24	72	4.72237E+21

If it takes 3 seconds to run a single simulation run of the model considering only one pump to be manipulated and only one leaking node to be observed. When more leaking nodes are considered this time can go higher.

Therefore, to test all possible combinations one by one (considering only one pump), it takes about 3 seconds X 16,777,216 = 50,331,648 seconds or (13,981 hours) or (582 days) or (One year and seven months).

Genetic algorithm is applied to determine an optimal pumping schedule which minimizes amount of leakage and energy consumption by pumps in Braila water distribution network with the constraints of satisfying service pressure at critical nodes.

3.5.5 Genetic Algorithms concepts applied to the optimization problem

Genetic algorithm simulates the biological genetics theory of natural selection to find better and better solutions with generations by implementing genetic operators such as recombination or cross over between good points, mutation to generate new points and selection of best performing points for next generation (Jonoski, 2020).

The following terms are used in genetic algorithms as defined below with an example of optimization of a single pump where zeros and ones represent OFF and ON statuses of the pump respectively for a total simulation time of 24 hours with a time step of 1 hour.

Population: is set of all vectors. For example, many pumping patterns

[

[1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0],

[1,1,1,1,1,0,1,1,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0],

[0,0,0,0,0,0,1,1,1,1,1,0,0,0,1,1,1,1,1,0,0,0,0,0],

[1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,1,1,1,0,0],

.

.

.

]

Chromosome: Each Point (vector). Example: one pumping pattern

[1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0]

Gene: Each Variable. Example: a single hour pump status

Ex: 1

Offspring: Children points created after recombination of best points (best performing pumping patterns) in the population. Best vectors are those that result in minimum objective function values.

Generations: is the allowable number of iterations to run the algorithm unless the minimum criteria is satisfied beforehand.

The steps of the genetic algorithm are listed below.

Initialization

Randomly initialize the population. Based on the defined number of populations it first randomly guesses vectors of possible solutions (Example: if the number of populations is defined to be one hundred, then 100 different random pumping patterns will be generated).

Fitness Evaluation

In this step, every suggested vector is evaluated for the objective functions. Example: each pumping pattern suggested in the population are used to run the EPANET model one by one and determine the resulting leakage amount for each of them. Therefore, each vector in the population will have its own functional value.

Selection

In the selection stage, those N points from the population which have minimum functional values are selected. For example: from the total of 100 vectors in the population, 50 best points will be selected and the rest 50 bad points will be disregarded. Here, best indicates those resulting in minimum leakage during the evaluation sorted ranking with ascending values of leakage. It should be noted that these best points should satisfy the requirement of satisfying the constraint. For example: the constraint of satisfying minimum service pressure in the network.

Crossover

In this stage, recombination will be made between the selected best points to create offspring and the number of population again becomes as it was initially. For example from the 50 selected points, best ones will be recombined to form another 50 offspring and which makes the total population to be used for the next generation again 100.

Cross over Example: Pattern 1 and Pattern 2 are among the best 50 points

Pattern 1 = [1,1,1,1,0,0,0,0,1,1,1,1,0,0,0,0,1,1,1,1,0,0,0,0]

Pattern 2 = [1,1,1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0]

Offspring 1 = [1,1,1,1,0,0,0,0,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0]

Offspring 2 = [1,1,1,1,1,1,1,1,1,1,1,1,0,0,0,0,1,1,1,1,0,0,0,0]

Offspring 1 is created by taking the first half of the chromosome from pattern 1 and the second half of the chromosome from pattern 2. Whereas, offspring 2 is created the other way around; the first half from pattern 2 and the second half from pattern 1.

Mutation

Modification is done on random genes of some vectors according to mutation operator. The mutation operator can be changing the gene reverse. For example if it was originally one, it will change it to zero and vice versa.

Example Mutation:

Pattern 2 = [1,1,1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0]

Mutated Pattern 2 = [1,1,1,1,1,1,0,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0]

The mutation operator changed randomly the seventh gene from one to zero (from status of ON to OFF).

This process continues iteratively until the minimum objective values are met or the number of generations is satisfied.

3.5.6 Model Based Optimization Flowchart

Figure 13 depicts the basic model-based optimization flowchart followed in the research. It is written in Python and is composed of three steps connected forming a loop. The first one is the genetic algorithm part which iteratively suggests a pumping pattern in an intelligent fashion to the second part of the code which manipulates the pumping pattern and runs the model and generates the outputs such as pressure at each node and total energy consumption by pumps. The third part of the code is the one calculating the leakage amount at each potential leaking nodes based on the pressure generated from the second part. And it supplies the calculated leakage and energy amounts to the first code which again uses these results as a basis to predict the next generation patterns to be used as a solution. This process continues until the stopping criteria is satisfied.

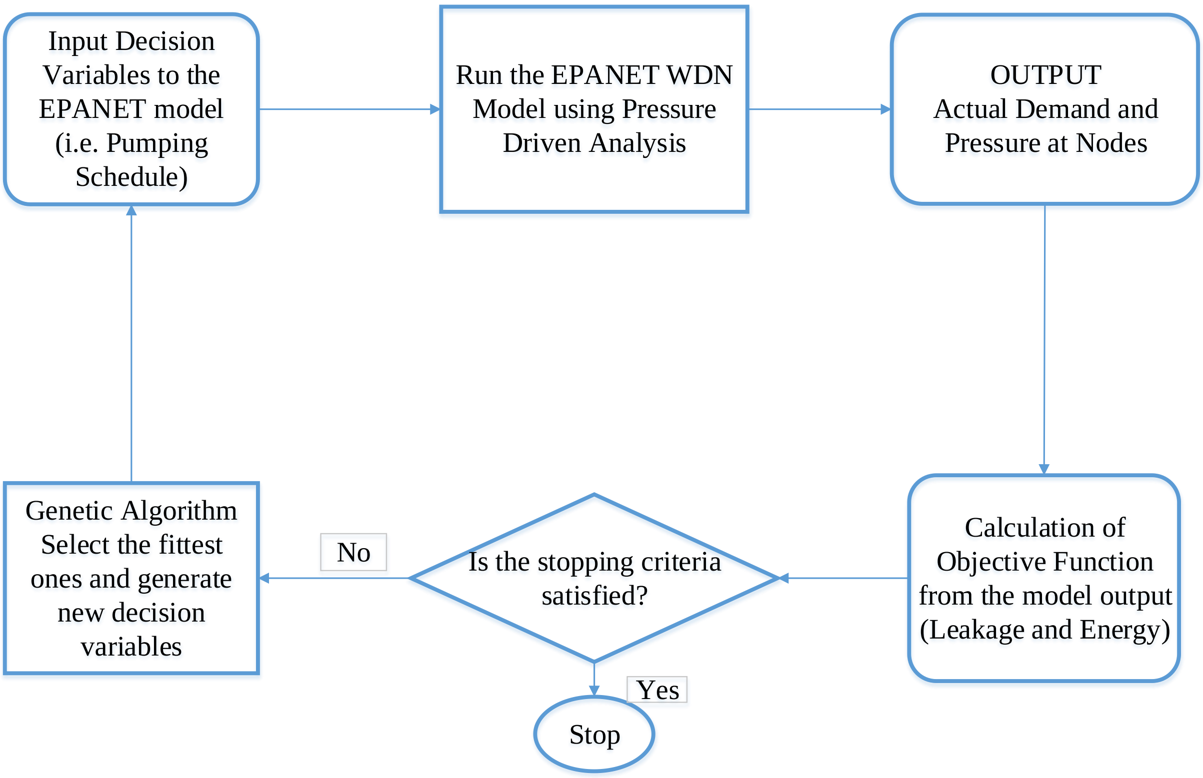


Figure 13 Basic Model Based Optimization Flowchart

3.6 Model modification to analyse leakage

The original, provided EPANET model of Braila WDN assumes leakage as a fixed percentage of the household consumption and allocates it as a second demand category. The modellers assumed a percentage of 81% which is applied at every junction in the network. For example, for a junction with a house hold consumption of 1.0 l/s, an extra 0.81 l/s is allocated to account for losses whose major component represents the physical losses (leakage).

The problem with this kind of representation of leakage is that it does not actually show the reality on the ground that leakage varies with the available pressure. It makes the model to show as if there is constant amount of leakage for any extent of pressure magnitude at the junction.

To resolve this problem, it was needed to replicate the model with a new one which represents leakage amount as a function of available pressure at the junction. This is done using an emitter, EPANET junction property. By means of assigning emitter coefficient and exponent parameters at selected leaking nodes in the network it is possible to simulate leakage at each junction.

Emitters represent flow through nozzle or orifices. They enable us to represent flow as a function of pressure as expressed in Equation 5.

3.6.1 Pressure-Leakage Relationship

Based on the expression of Equation 5, pressure versus leakage rate relationship can be plotted as shown in Figure 14 for different cases of emitter coefficient and emitter exponent combinations.

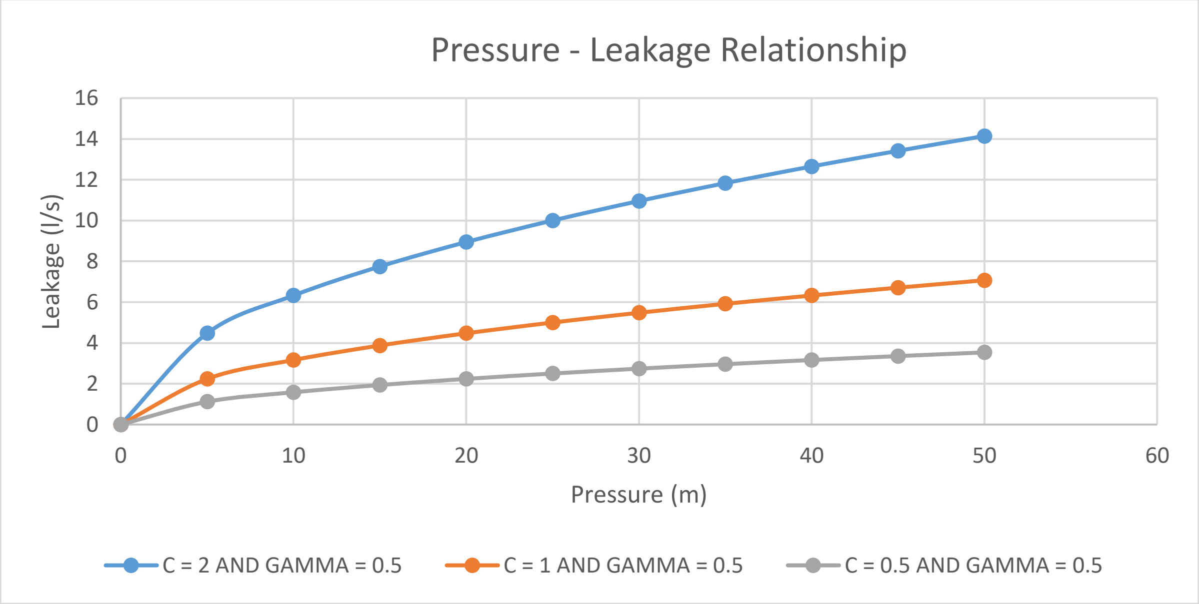


Figure 14 Leakage-Pressure Relationship for different cases of emitter coefficient and exponent

3.6.2 Model Replication

In order to replace the constant leakage demand in the original model with a pressure dependent leakage demand, the first thing which was done was determining potential leakage areas in the network so that emitters will be placed on them. And the second thing is determining emitter coefficient and emitter exponent values for each considered potential leaking nodes in such a way that the resulting total leakage amount becomes equivalent to that of the original model.

Determination of the emitter coefficients and emitter exponent was done using weighted proportioning of the total leakage in the network to the selected leaking nodes based on their average pressure from the original model run. The reason behind this assumption is that nodes with higher pressure are expected to experience greater amount of leakage. After proportioning the total leakage to each leaking nodes, by assuming one emitter exponent for the whole network, it was possible to determine the emitter coefficient, C, value for each considered leaking nodes using Equation . Equation 8 shows how the emitter coefficient at each potential leaking node was determined.

$$C = \frac{q}{\sqrt{P}}$$ *Equation 8 Emitter Coefficient*

Figure 15 depicts the process flowchart for the replication of the model.

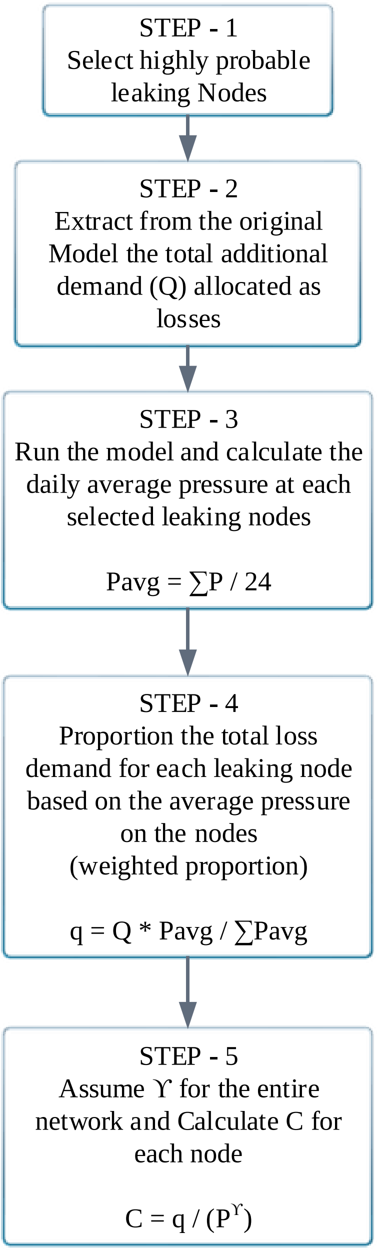


Figure 15Model Replication Steps Flowchart

Firstly, 28 nodes were selected as potential leaking nodes based on some rules as it is elaborated in Section 3.7. Then, with a Python script, employing the WNTR module it was possible to extract the allocated loss demands at each node in the original network model and summing them up total leakage rate in the network was found out to be 131 l/s.

The next step was determining the average daily pressure at each leaking nodes and proportioning this total leakage to the each of them based on their available pressure and this was done as shown in Table 8.

Table 8 Emitter Coefficients Determination

	Leaking Node id	**Average Pressure, Pavg = ∑P /24**	**Leak Demand, q = Qtot * Pavg / ∑Pavg**	**Coefficient, C = q / (Pavg$^{\Upsilon}$)**
1	1_11	10.01	10.01	0.179
2	wNode_4063	12.57	12.57	0.171
3	wNode_433	21.32	21.32	0.154
4	wNode_1759	10.30	10.30	0.178
5	wNode_417	9.94	9.94	0.179
6	wNode_1915	10.71	10.71	0.177
7	wNode_1134	11.00	11.00	0.176
8	wNode_209	6.48	6.48	0.195
9	wNode_2032	11.61	11.61	0.174
10	wNode_1875	15.02	15.02	0.165
11	1_20	10.86	10.86	0.176
12	1_90	6.65	6.65	0.194
13	wNode_1126	12.83	12.83	0.17
14	wNode_1807	10.09	10.09	0.179
15	wNode_831	22.99	22.99	0.152
16	1_419	22.36	22.36	0.153
17	wNode_1470	22.36	22.36	0.153
18	wNode_650	21.63	21.63	0.154
19	wNode_2860	21.45	21.45	0.154
20	wNode_636	21.21	21.21	0.154
21	wNode_971	21.19	21.19	0.154
22	wNode_3777	21.14	21.14	0.154
23	wNode_2360	21.04	21.04	0.154
24	wNode_932	20.95	20.95	0.155
25	wNode_1	20.58	20.58	0.155
26	wNode_990	20.62	20.62	0.155
27	1_163	20.41	20.41	0.155
28	wNode_2116	20.41	20.41	0.155

3.7 Rule-based selection of leakage points

In order to incorporate leakage to the existing model using pressure driven analysis, it is necessary first to determine the locations of leaking nodes. However, the positions of these leaking nodes are not exactly known. Therefore, some rules are used in this research to make a technical guess on these locations, involving traffic load, diameter of pipes, historical data of reparations and pressure, as described in the sections below.

3.7.1 External Pressure from traffic Load

The first rule assumes that there is high probability for a pipe burst when the pipes are laid below high external pressure from traffic load. Heavy traffic load affects pipes especially those with low diameter (Așchilean, et al., 2018).

In order to determine pipes beneath highways, QGIS spatial analysis software is used. First the EPANET model of the Braila water distribution network is converted to a shape file by means of the QGIS plugin “Import EPANET input file”. Then, from open street map which is a freely available editable world map, different classes of highway network maps lying within the boundary of Braila city are imported as shape files. The major highway classes available in the city are Trunk roads, Primary roads, Secondary roads and Tertiary roads listed with decreasing traffic load and importance respectively. Definitions of the considered highway classes taken from the open street map features is presented in Table 9.

Table 9 Highway classification lying within Braila City

Highway Type	**Definition**
Trunk	The most important roads in a country's system that aren't motorways. (Need not necessarily be a divided highway.)
Primary Roads	The next most important roads in a country's system. (Often link larger towns.)
Secondary Roads	The next most important roads in a country's system. (Often link towns.)
Tertiary Roads	The next most important roads in a country's system. (Often link smaller towns and villages)

Figure 16 portrays the traffic map of Braila city classified with highway type.

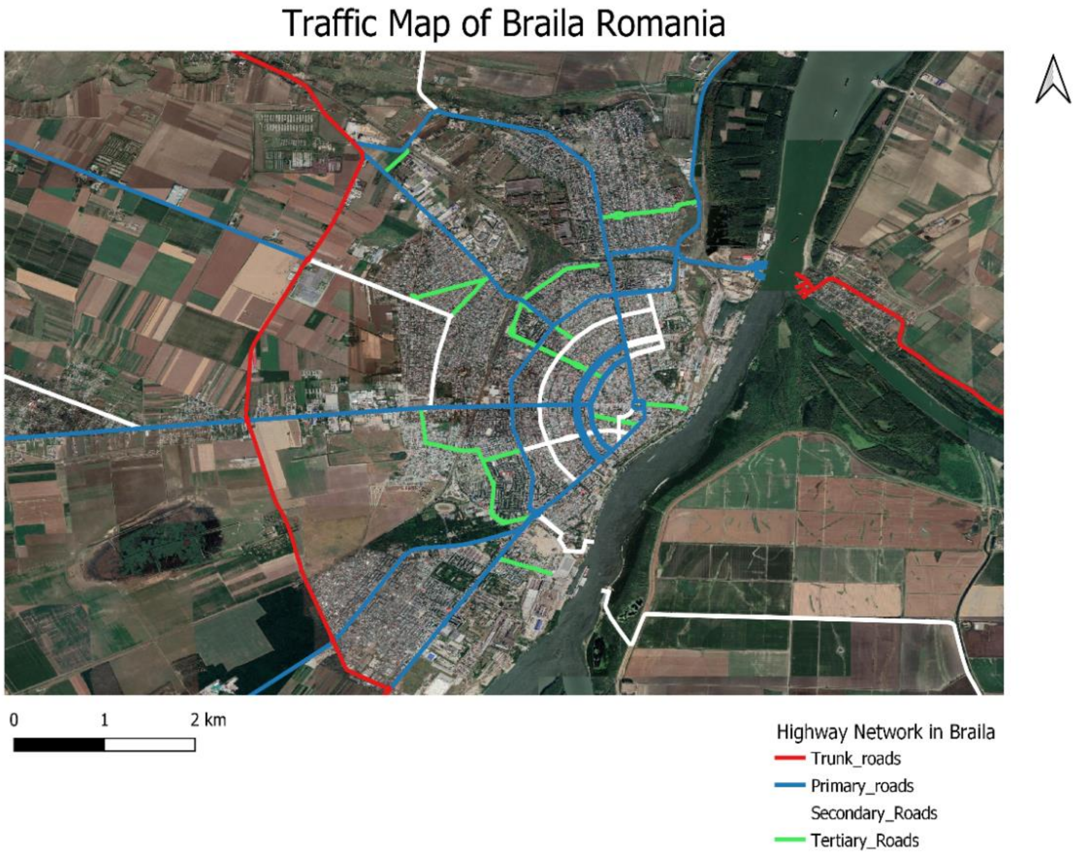


Figure 16 Traffic Map of Braila City

Then the ‘Vector overlay’ tool is employed to determine the crossing points (intersection points) of pipes with highways. As a result, from the total of 3184 pipes, 485 pipes are found to be overlaid by highways of which 27 intersect with trunk roads, 236 intersect with primary roads, 112 intersect with secondary roads and 110 pipes intersect with tertiary roads. Figure 17 and Figure 18 show the pipe network of the city and traffic map overlying on the pipe network respectively.

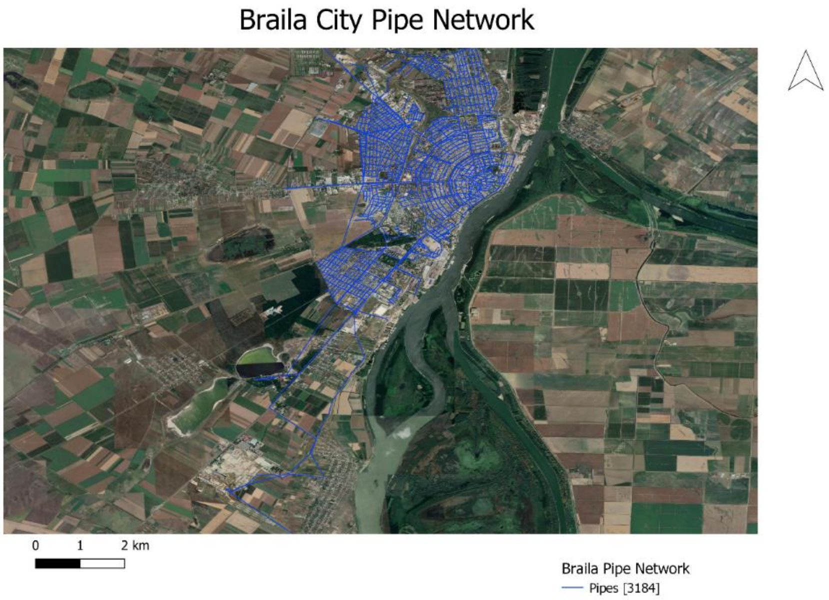


Figure 17 Braila City Pipe Network

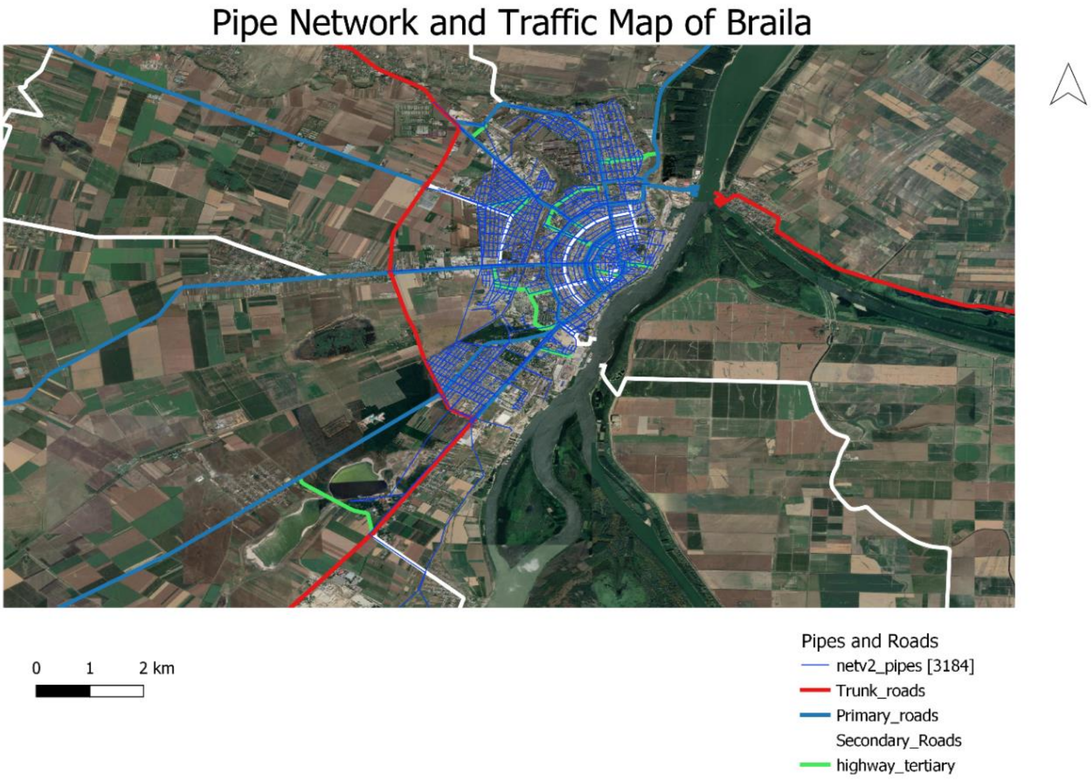


Figure 18 Traffic Map overlaying on Pipe Network of Braila City

3.7.2 Diameter of Pipes

The second rule is based on the fact that diameter of pipes affect the likelihood of occurrence of pipe burst (Saghi, 2015). Longer and smaller diameter pipes are more likely to suffer from leakage than those that are short and larger diameter pipes.

Critical diameter and length of pipes are established for each category of pipes overlaid by traffic loads so as to filter the most sensitive pipes. If a pipe has less diameter than the critical diameter and longer than the critical length, then it will be considered as potential leaking pipe. Those pipes lying under trunk roads are more sensitive than those lying under primary or secondary roads as the traffic load is greater on trunk roads. Therefore, a relatively larger pipe diameter and a shorter pipe length are fixed as critical diameter and length for trunk roads. The same principle which is heaviness of traffic load is taken in to consideration while defining the critical parameters for each categories of pipes. Table 10 lists the considered critical diameter and length for each highway category.

Table 10 Critical Length and Diameter of Pipes

	Pipes Overlaid by			
	Trunk Roads	Primary Roads	Secondary Roads	Tertiary Roads
Critical Length(m)	300	320	330	400
Critical Diameter(mm)	210	100	100	100

The defined length and diameter are then utilized to select the most probable pipes to possess leaking cracks and bursts from the 485 pipes which intersect with major roads. Based on these criteria of external pressure, length and diameter, a list of 18 pipes are screened out as potential leakage pipes presented on Table 11.

Table 11 Potential Leaking Pipes screened with Traffic Load, Length and Diameter

Intersecting Road	Pipe id
Trunk	1_255
	wLink_1275
	wLink_2658
	wLink_3129
Primary	1_210
	1_220
	wLink_1418
	wLink_1980
	wLink_2128
	wLink_2993
Secondary	wLink_1425
	wLink_1430
	wLink_3326
Tertiary	wLink_2049
	wLink_1266
	wLink_2088
	wLink_3575
	1_258

3.7.3 Internal Pressure

Thirdly, the available pressure on nodes from original model demand driven analysis can indicate that the magnitude of leakage on the pipes linked to that node can be higher as it was calibrated with measured values of pressure. Those Nodes with pressure amount of above 25 meter during critical time of the day (03:00 O'clock) are considered as high potential areas for leakage. Based on this, 14 nodes were found to experience pressure above 25 m at time (03:00 O'clock). Table 12 presents nodes with high pressure in the network.

Table 12 Nodes screened out using Pressure resulting from Demand driven Analysis

DESCRIPTION			
Pressure > 25 m at 03:00am	**Demand**	**Head**	**Pressure**
Node ID	**LPS**	**m**	**m**
Junc wNode_831	0.01	32.7	27.7
Junc 1_419	0.01	33.51	26.65
Junc wNode_1470	0	33.51	26.65
Junc wNode_650	0.04	33.23	26.46
Junc wNode_2860	0.01	30.63	26.13
Junc wNode_636	0.04	34.29	25.95
Junc wNode_971	0.04	34.58	25.87
Junc wNode_3777	0.04	30.63	25.82
Junc wNode_2360	0	31.92	25.72
Junc wNode_932	0.05	34.61	25.61
Junc wNode_1	0.01	34.58	25.43
Junc wNode_990	0.01	31.18	25.31
Junc 1_163	0.01	34.58	25.25
Junc wNode_2116	0.02	34.58	25.25

3.7.4 Historical reparation Data

The fourth rule is based on previous reparation history. Areas with history of excessive leaks and break rates have higher potential to experience leakage all over again. And it was managed to get reparation data from the Braila city's water utility especially the Radu Negru DMA. Figure 19 depicts the historical reparation points of the Radu Negru district metring area of Braila water distribution Network.

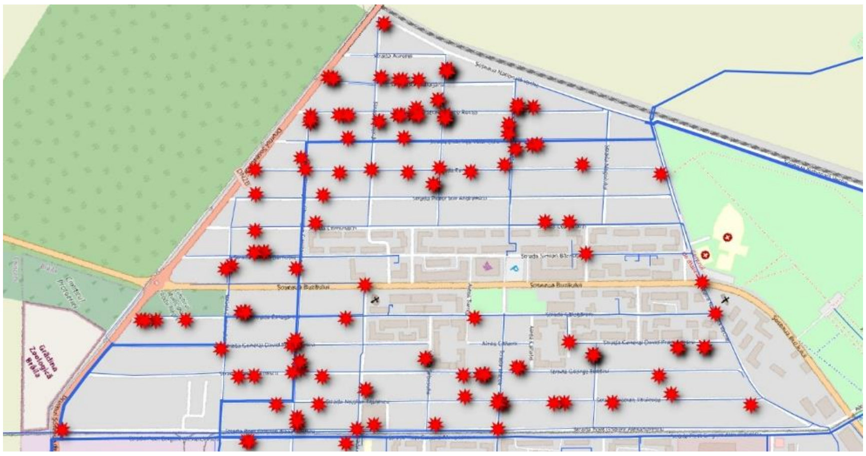


Figure 19 Historical Reparation locations of Radu Negru DMA

Finally, the potential leaking node sets selected with the four criteria were merged into one as presented in Table 13.

Table 13 Finally Selected Potential Leaking Nodes in Braila Water Distribution Network

Selected Node	Reason
Junc wNode_831	High Pressure from DD Analysis
Junc 1_419	High Pressure from DD Analysis
Junc wNode_1470	High Pressure from DD Analysis
Junc wNode_650	High Pressure from DD Analysis
Junc wNode_2860	High Pressure from DD Analysis
Junc wNode_636	High Pressure from DD Analysis
Junc wNode_971	High Pressure from DD Analysis
Junc wNode_3777	High Pressure from DD Analysis
Junc wNode_2360	High Pressure from DD Analysis
Junc wNode_932	High Pressure from DD Analysis
Junc wNode_1	High Pressure from DD Analysis
Junc wNode_990	High Pressure from DD Analysis
Junc 1_163	High Pressure from DD Analysis
Junc wNode_2116	High Pressure from DD Analysis
1_255	Intersection with Trunk Road and Critical D and L
wLink_1275	Intersection with Trunk Road and Critical D and L
wLink_2658	Intersection with Trunk Road and Critical D and L
wLink_3129	Intersection with Trunk Road and Critical D and L
1_210	Intersection with Primary Road and Critical D and L
1_220	Intersection with Primary Road and Critical D and L
wLink_1418	Intersection with Primary Road and Critical D and L
wLink_1980	Intersection with Primary Road and Critical D and L
wLink_2128	Intersection with Primary Road and Critical D and L
wLink_2993	Intersection with Primary Road and Critical D and L
wLink_1425	Intersection with Secondary Road and Critical D and L
wLink_1430	Intersection with Secondary Road and Critical D and L
wLink_3326	Intersection with Secondary Road and Critical D and L
wLink_2049	Intersection with Tertiary Road and Critical D and L
wLink_1266	Intersection with Tertiary Road and Critical D and L
wLink_2088	Intersection with Tertiary Road and Critical D and L
wLink_3575	Intersection with Tertiary Road and Critical D and L
1_258	Intersection with Tertiary Road and Critical D and L

3.8 Experiment Design

Before designing the experiments, tracing was done to determine the area of nodes which are supplied by each pumps in the network. This helps in determination of the possible pumps to optimize in the network. It was found out that four of the pumps (wLink_5794, wLink_5796, wLink_5800 and wLink_5825) pump water from the Danube River to the Treatment plant and from the treatment plant to the three reservoirs which are in Braila, Apollo and Radu Negru respectively. The rest two pumps (wLink_5805 and wLink_5806) supply directly the nodes in the network by pumping water from the Braila and Apollo storage complexes. The four pumps supplying the reservoirs should be ON throughout the day and hence can't have pump schedules. Therefore, only the other two pumps which feed the network directly (wLink_5805 and wLink_5806) are considered for optimization.

Three experiments were designed to understand how the optimal scheduling behaves in the cases of real-time operations. The first one is consists of initial experiment cases which are aimed at selection of the optimization approach. Whereas, the focuses of the second and the third experiments are to investigate the effect of water demand variation and the effect of applying pressure driven analysis optimal scheduling respectively.

The first experiment has two cases considering multi objective optimization and single objective optimization approaches separately as presented in Table 14. This experimental design was made as an initial experiment to determine the suitable optimization approach.

Table 14 Experiment 1 (Initial Experiments)

No	Case	Description	Algorithm	Expected Output	Message to be extracted
1	MOO with Objective Functions: Minimizing Leakage and Energy Consumption)	Optimization of Pumps wLink_5805 and wLink_5806	NSGAII	Optimal Pump Schedule	To check the need for MOO
				Minimum Leakage Volume that could be achieved	
				Minimum Energy consumption that could be achieved	
2	Single Objective Optimization (Objective Function: Minimizing Leakage)	Optimization of Pumps wLink_5805 and wLink_5806	NSGAII	Optimal Pump Schedule	To check the SOO approach
				Minimum Leakage Volume that could be achieved	
				Resulting Energy consumption as a result of applying optimal schedule	

The second experiment considers real time variation of water demand in the system. Therefore, it is arranged in order that it enables to make analysis on the effect of water demand variation on optimal schedule of the pumps, minimum leakage, and minimum energy. And hence, the experiment is done for seven demand cases running the optimization of the pump in Braila DMA (wLink_5805) which is feeding the network directly. In this experiment, in addition to the typical demand, the optimization run is implemented for demand magnitude with 5%, 10% and 15% deviation (up/ down) from the typical demand as expressed on Table 15.

Table 15 Experiment Design 2 (Variation of Water Demand)

No	Case	Description	Algorithm	Expected Output	Message to be extracted from the Experiment
1	15 Percent Less demand than the Typical Demand	Optimization of Pump wLink_5805	NSGAII	Optimal Pump Schedule Minimum Leakage Volume that could be achieved Minimum Energy consumption that could be achieved	To investigate the effect of demand variation on optimal pump schedule, Minimum Leakage and Minimum Energy
2	10 Percent Less demand than the Typical Demand	Optimization of Pump wLink_5805	NSGAII	Optimal Pump Schedule Minimum Leakage Volume that could be achieved Minimum Energy consumption that could be achieved	To investigate the effect of demand variation on optimal pump schedule, Minimum Leakage and Minimum Energy
3	5 Percent Less demand than the Typical Demand	Optimization of Pump wLink_5805	NSGAII	Optimal Pump Schedule Minimum Leakage Volume that could be achieved Minimum Energy consumption that could be achieved	To investigate the effect of demand variation on optimal pump schedule, Minimum Leakage and Minimum Energy
4	Typical Demand	Optimization of Pump wLink_5805	NSGAII	Optimal Pump Schedule Minimum Leakage Volume that could be achieved Minimum Energy consumption that could be achieved	To investigate the effect of demand variation on optimal pump schedule, Minimum Leakage and Minimum Energy
5	5 Percent More demand than the Typical Demand	Optimization of Pump wLink_5805	NSGAII	Optimal Pump Schedule Minimum Leakage Volume that could be achieved Minimum Energy consumption that could be achieved	To investigate the effect of demand variation on optimal pump schedule, Minimum Leakage and Minimum Energy
6	10 Percent More demand than the Typical Demand	Optimization of Pump wLink_5805	NSGAII	Optimal Pump Schedule Minimum Leakage Volume that could be achieved Minimum Energy consumption that could be achieved	To investigate the effect of demand variation on optimal pump schedule, Minimum Leakage and Minimum Energy
7	15 Percent More demand than the Typical Demand	Optimization of Pump wLink_5805	NSGAII	Optimal Pump Schedule Minimum Leakage Volume that could be achieved Minimum Energy consumption that could be achieved	To investigate the effect of demand variation on optimal pump schedule, Minimum Leakage and Minimum Energy

The third experiment is formatted in order to assess the effect of implementation of pressure driven analysis instead of the customary demand driven analysis. In this experiment, variation is done in the required pressure which is used for pressure driven analysis of the model. In order to do this, the experiment sets five cases of required pressure which are when the required pressure is 0.1m, 1m, 3m, 5m and 10m as seen on Table 16 and each case was checked separately. The case with required pressure of 0.1m somehow simulates the demand driven analysis.

Table 16 Experiment Design 3 (Variation in Required Pressure)

No	Case	Description	Algorithm	Expected Output	Message to be extracted from the Experiment
1	Required Pressure 0.1m	Optimization of Pump wLink_5805	NSGAII	Optimal Pump Schedule Minimum Leakage Volume that could be achieved Minimum Energy consumption that could be achieved	To investigate the effect of required pressure variation on optimal pump schedule, Minimum Leakage and Minimum Energy
2	Required Pressure 1m	Optimization of Pump wLink_5805	NSGAII	Optimal Pump Schedule Minimum Leakage Volume that could be achieved Minimum Energy consumption that could be achieved	To investigate the effect of required pressure variation on optimal pump schedule, Minimum Leakage and Minimum Energy
3	Required Pressure 3m	Optimization of Pump wLink_5805	NSGAII	Optimal Pump Schedule Minimum Leakage Volume that could be achieved Minimum Energy consumption that could be achieved	To investigate the effect of required pressure variation on optimal pump schedule, Minimum Leakage and Minimum Energy
4	Required Pressure 5m	Optimization of Pump wLink_5805	NSGAII	Optimal Pump Schedule Minimum Leakage Volume that could be achieved Minimum Energy consumption that could be achieved	To investigate the effect of required pressure variation on optimal pump schedule, Minimum Leakage and Minimum Energy
5	Required Pressure 10m	Optimization of Pump wLink_5805	NSGAII	Optimal Pump Schedule Minimum Leakage Volume that could be achieved Minimum Energy consumption that could be achieved	To investigate the effect of required pressure variation on optimal pump schedule, Minimum Leakage and Minimum Energy

Chapter 4 Experiment and Results

This chapter presents the results of the experiments explained in section 3.8.

4.1 Multi Objective Optimization (MOO) and Single Objective Optimization (SOO) Results (Experiment 1)

Initially, the optimization was posed as a multi objective problem to solve for a pump schedule which minimizes total leakage volume and energy consumption for pumps wLink_5805 and wLink_5806. However, it was discovered from different multi-objective optimization (MOO) runs that, for this specific water distribution network, the objective functions, of minimizing leakage and minimizing energy consumption appeared to be non-conflicting objectives. And as a solution, instead of multiple Pareto fronts, only one point (solution) tend to satisfy the requirement of non-dominated solution minimizing both of the objectives functions as shown in Figure 20.

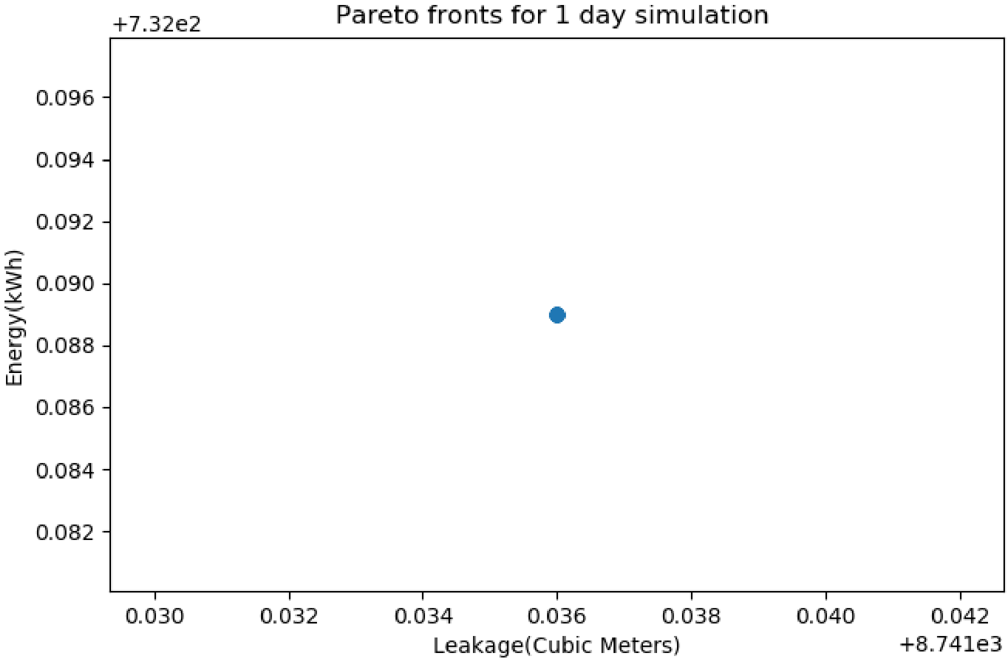
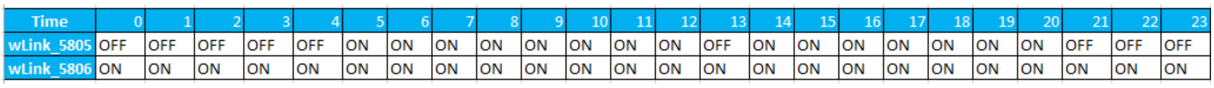


Figure 20 Pareto Front for MOO pump wLink_5805

The resulting pump schedule for the considered pumps (wLink_5805 and wLink_5806) is presented on Table 17.

Table 17 Pump Schedule for wLink_5805 and wLink_5806 as a result of MOO run



Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
wLink_5805	OFF	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON	OFF	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF
wLink_5806	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON

Then, a shift was made from the MOO into a single objective optimization (SOO) run considering only minimization of total leakage volume as an objective function. The energy consumption was then calculated to the resulting optimal solutions and reported separately. The computation time is reduced almost by half while achieving to get the solution which minimizes both of the objective functions.

Therefore, a SOO was run to optimize pumps wLink_5805 and wLink_5806 with the following attributes.

Objective Function: Minimizing total leakage volume during the 24 hrs

Algorithm: NSGA II

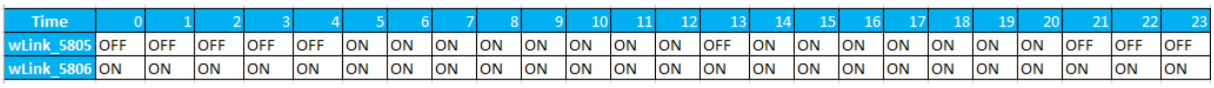
Population Size = 50

Number of generations = 4000

Pumps Location = Braila (wLink_5805) and Apollo (wLink_5806)

With this experiment, it was observed from the optimal pump schedule that the pump in Apollo (wLink_5806) should be twenty-four hours ON while the pump in Braila (wLink_5805) can be OFF for nine hours of the day as shown in Table 18.

Table 18 Pump Schedule for wLink_5805 and wLink_5806 as a result of SOO run



Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
wLink_5805	OFF	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON	OFF	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF
wLink_5806	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON

Therefore, as the pump in Apollo should always be ON, it doesn't need to be included in the optimization anymore and the next experiments were done for only pump wLink_5805 so that the computation time becomes way lesser.

4.2 Results of SOO considering different magnitudes of Demand (Experiment 2)

This experiment is based on the experiment design 2 described on section 3.8. The SOO run was done considering minimization of leakage as the single objective function and considering different magnitudes of demands. To run these experiments, first the demand of the base model is multiplied with the desired percentage assumed to deviate from the typical demand. Then the model with an altered demand pattern is saved as new model and this new model is used during the optimization. A total of seven optimization runs were made considering the conditions of the typical demand and 5%, 10% and 15% increase as well as decrease from the typical demand in all the nodes. All the seven tests were made assuming a required pressure of 0.1m, minimum pressure of 0 m.

The purpose of this experiment is to investigate water demand variation on optimal pumps operation and on the minimum possible leakage thereby simulating the real-time optimized operation of the system.

After running the seven cases, optimal pumping schedules were obtained. The optimal leakage amounts and the energy consumption occurring as a result of applying the optimal pump schedules for each case are presented in Table 19. The average time taken to run each case was 4700 seconds.

Table 19 Leakage and Energy Consumption Results for different demand cases

Demand Cases	**Optimized Leakage (m3)**	**Resulting Energy Consumption (kWh)**	**Experiment Case Representation**
15 Percent Less demand than the Typical	8336.547	6364.274	E2C1
10 Percent Less demand than the Typical	8437.111	6509.948	E2C2
5 Percent Less demand than the Typical	8295.789	6509.948	E2C3
Typical Demand	8275.586	6581.224	E2C4
5 Percent More demand than the Typical	8134.411	6581.224	E2C5
10 Percent More demand than the Typical	8115.181	6650.986	E2C6
15 Percent More demand than the Typical	7974.526	6650.986	E2C7

These results are plotted and discussed in the discussion part, section 5.2.

Originally when the pumps were all ON twenty four hours a day, the leakage and energy consumption was as presented in Table 20.

Table 20 Leakage Volume and Energy Consumption with custom operation

Total Leakage When All pumps are turned on 24 hrs	8061.19	m^3
Total Energy Consumption by all pumps ON 24 hrs	7143.39	kWh

Table 21 shows the optimal pumping schedules for wLink_5805 considering each demand cases. The demand case names can be referred on Table 19.

Table 21 Optimal Pump Schedule of Pump in Braila Station (wLink_5805) for different demand cases

	Optimal Pump Schedule for Pump in Braila Station (wLink_5805)																							
	Time of the day (hr)																							
Demand Case	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
E2C1	OFF	OFF	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF
E2C2	OFF	OFF	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	OFF	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF
E2C3	OFF	OFF	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	OFF	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF
E2C4	OFF	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON	OFF	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF
E2C5	OFF	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON	OFF	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF
E2C6	OFF	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF
E2C7	OFF	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF

4.3 SOO considering different magnitudes of required pressure used in PDD

Results of experiment design 3, described in section 3.9, is presented below. This experiment is considering different required pressure cases with the aim at scrutinizing the effect of using the pressure driven analysis and the sensitivity of system for the parameter of required pressure. The considered required pressure values are 0.1m, 1m, 3m, 5m and 10m. The first case with required pressure of 0.1m is nearly similar to demand driven analysis since with this required pressure all requested amount of demand can be supplied.

All the five cases were run considering a minimum pressure of 1.5m. After running the optimization for each case of required pressure cases the optimal pumping schedule are shown on Table 23 and the achieved minimum leakage volume values with the corresponding energy consumption amounts are described in Table 22.

Table 22 Leakage and Energy consumption results for different cases of required pressure

Required Pressure case for Pressure Driven Analysis	Optimized Leakage (m3)	Resulting Energy Consumption (kWh)	Constraint Violation Pressure (m)	Experiment Case Representation
Required Pressure = 0.1m	8741.036	6851.05	0.3725	E3C1
Required Pressure = 1m	8838.47	6905.49	0.3725	E3C2
Required Pressure = 3m	8743.271	6851.35	0.157	E3C3
Required Pressure = 5m	8767.059	6856.69	0	E3C4
Required Pressure = 10m	8729.199	6772.91	0	E3C5

Table 23 Optimal Pump Schedule for pump in Braila station (wLink_5805) with different 'required pressure' cases of pressure driven analysis

	24 hrs Optimal Pump Schedule for Pump in Braila Station (wLink_5805)																							
	Time of the day (hr)																							
Required Pressure Case	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
E3C1	OFF	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON	OFF	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF
E3C2	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	OFF
E3C3	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	OFF
E3C4	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	OFF
E3C5	OFF	OFF	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	OFF	OFF

Chapter 5 Analysis and Discussion

In this chapter, the results reported in the previous chapter are analysed and discussed. It starts with comparison of energy and leakage results for existing and optimal operations. Then, it discusses comparison of different demand cases, followed by comparison of different required pressure cases. Afterwards, pressure time graph comparison is analysed for the cases of existing operation, optimal operation as well as different demand and required pressure cases. Finally, a real time operational framework is suggested and discussed.

5.1 Leakage and Energy consumption comparison between existing operation and optimal operation

Pump wLink_5805, located near Braila storage house, together with pump wLink_5806 which is located near the Apollo water house, feed the network directly by pumping water from the storage water houses in Braila and Apollo respectively. The results indicate that the pump in Apollo should always be ON so that the minimum service pressure can be achieved. Whereas, on the other hand, the experiments show that it is possible to play with the pump in Braila to minimize the leakage amount while maintaining the service pressure.

The optimization result displays that the optimal operation results in a 12 % minimization of leakage volume relative to the existing operation. Table 24 presents the total leakage volume and energy consumption results corresponding to the custom and optimal operation of pump wLink_5805 as well as the energy and water saving percentages due to the optimal operation.

Table 24 Leakage and Energy Consumption comparison between existing and optimal operations

Operation Type	**Leakage (m3)**	**Energy (kWh)**
Custom Operation	9363.786	7143.386
Optimal Operation	8275.586	6581.224
Percentage Saving	11.62%	7.87%

Figure 21 illustrates the percentage saving of leakage and energy considering the existing operation as 100%.

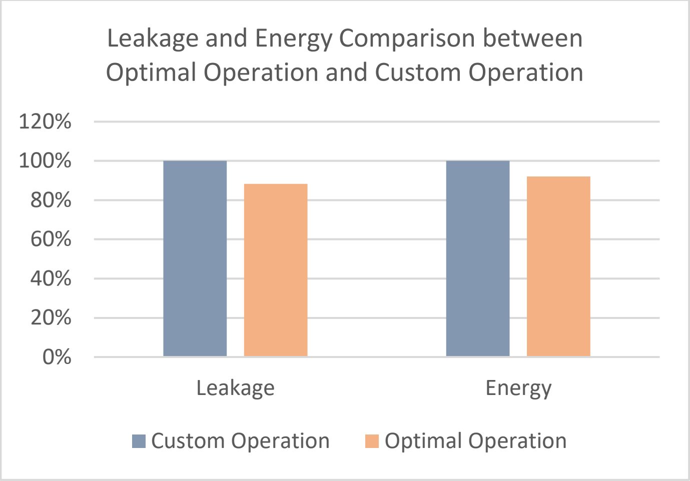


Figure 21 Leakage and Energy Consumption comparison in percentage between existing and optimal operations

5.2 Comparison between optimization results of different demand cases

The water demand variation affects the minimum leakage amount that could be achieved by operating the pumps with the optimal schedule. As the demand becomes far lower than the typical demand, the optimization results in a more frequent OFF values of the pump since it does not need to supply as much water as the typical demand. The average pressure on the distribution network is affected with this phenomenon in two opposing ways. On the one hand, the fact that pumps being OFF more frequently tends to reduce the pressure. On the other hand, the lowering of the demand tends to lower the flow in pipes and hence increasing the pressure which is in line with Bernoulli’s principle. The minimum leakage volume which can be attained by optimization depends on which of the two opposing factors magnifies. When the factor that reduces the pressure dominates the factor which raises the pressure, then the minimum leakage volume achieved in this demand case will be smaller than that of the typical demand case. Whereas, when the factor that increases the pressure prevails, then the minimum leakage volume that can be achieved in this case becomes higher than that of the typical demand case. The same principle works regarding to the demand scenarios with more demand than the typical.

From Figure 22, it can be noticed that, in all the three cases which have lower demand than the typical demand, the minimum total leakage volume that can be attained with optimization of pump wLink_5805 is greater than that of the typical demand scenario. But compared to one another, the scenario with 10% less demand brings about a greater minimum possible leakage volume than that of the case with a 15% less demand which means in this case the fact that the pump is OFF more frequently in the latter case determines the pressure and hence the leakage. On the other hand, the case with 5% less demand than the typical produces a less amount of attainable minimum leakage than the situation with 10% less demand than the typical indicating that, here, the reduction of flow in the pipes with the latter scenario prevails.

And those scenarios with more demand than the typical show a lower amount of minimum possible leakage. This indicates that, in these particular cases, the factor reducing pressure, which is the increased frequency of pumps being OFF, overrules the factor which raises up the pressure, which is lowered flow in the pipes.

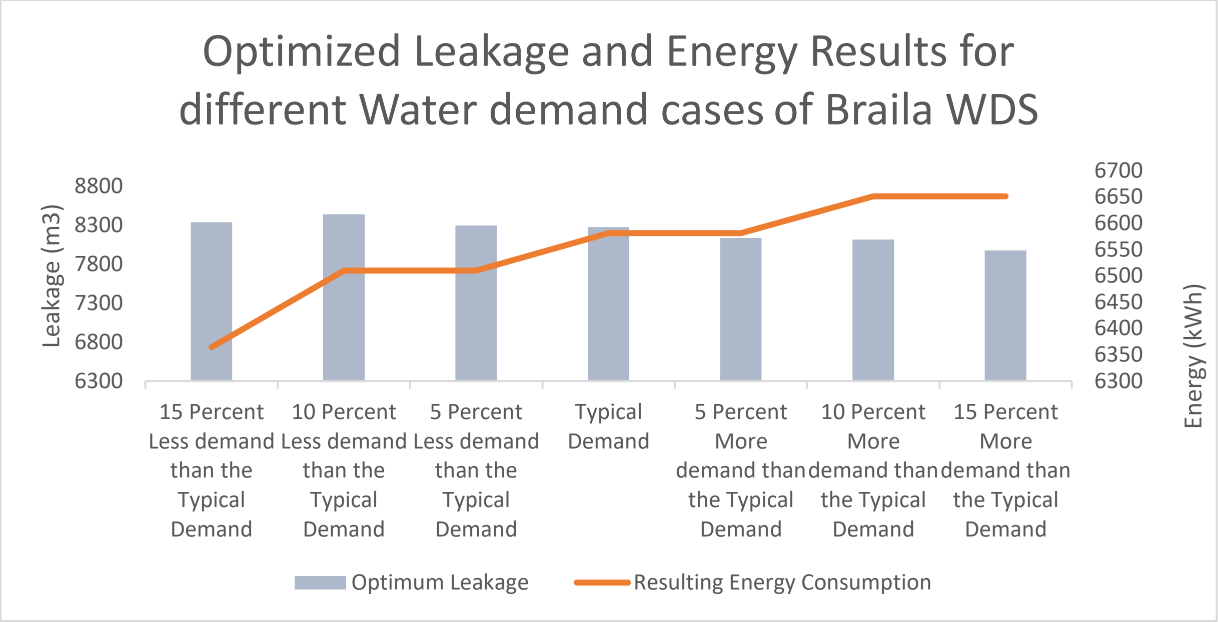


Figure 22 Optimum Leakage and Energy Results considering different demand cases

The energy consumption resulting from the application of the optimal schedules, shows that, in general, as the demand amount increases, the energy consumption by pumps also increases. However, in some scenarios it stays the same. For instance, the case with 10% more demand than the typical requires equal amount of energy to the case with 15% more demand than the typical. This is because, the two scenarios have the same optimal pump schedules.

5.3 Comparison between optimization results of different cases of required pressure in PDA

The “required pressure” parameter in the pressure driven demand analysis determines how much demand a node is supplied at any time. Unlike demand driven hydraulic analysis, the base demands assigned to each node in the network are not guaranteed to be supplied with the pressure driven hydraulic analysis. Rather, the demand which will be supplied to the node is dependent on the available pressure on the node at that particular time as discussed in section 3.4.2.

When the required pressure is higher, there will be relatively less possibility of supplying the total requested amount of demand since the available pressure at the nodes may be smaller than the required pressure. And, this leads to smaller flow in pipes since the flow leaving the network gets smaller. And this in turn causes the pressure in the network to be higher and thereby increasing the leakage rate. And on the contrary, since less demand flow is being released, the optimization algorithm tries to minimize the frequency of the pump status turned ON. This minimizes the pressure in the network and makes the optimal leakage to be lower. These two contrary situations occur simultaneously and one or the other dominates according to the situation. Thus, it makes the relationship between required pressure and optimal leakage volume to be dynamic.

Figure 23 demonstrates the optimal leakage variation with different scenarios of required pressure used during the hydraulic analysis. The energy required when operating with the optimal operations is also presented with a second axis.

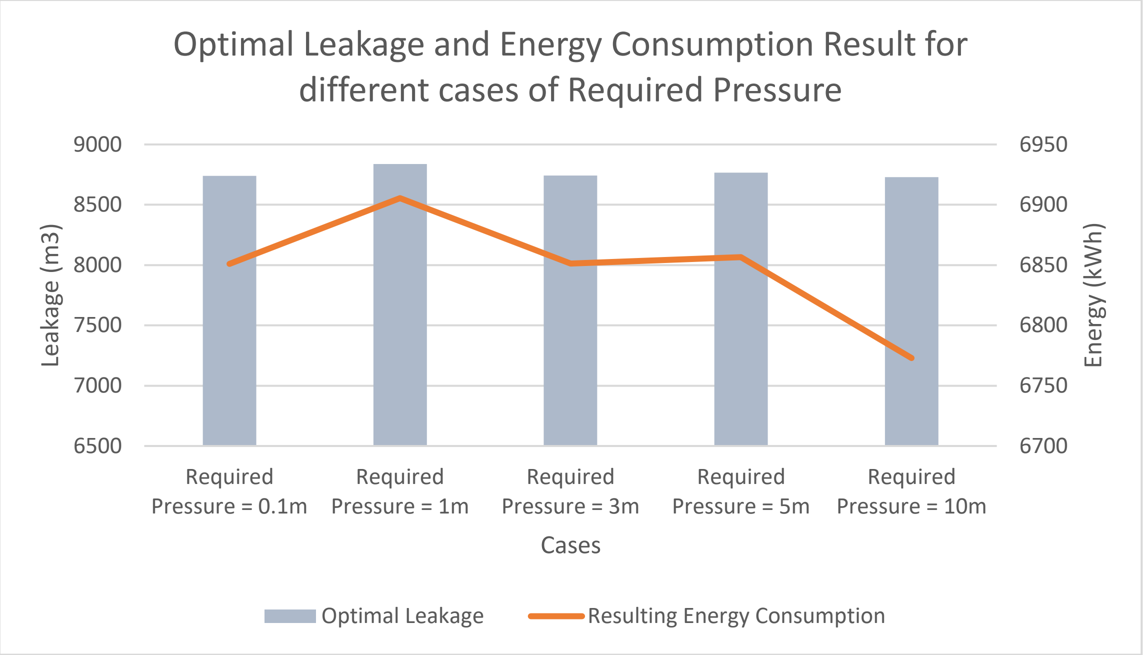


Figure 23 Comparison of optimization results for different cases of required Pressure

It is seen in Figure 23 that the optimal leakage volume rises as the required pressure is changed from 0.1m to 1m. The reason behind the increase in the minimum leakage is that with the latter case, the optimal pump schedule makes the pump wLink_5805 to be 20 hours ON out of the 24 hours of the day, while the case with required pressure of 0.1m resulted in a pump pattern which makes the pump ON for only 15 hours of the day. This makes the one-meter required pressure scenario to exhibit more pressure in the network and hence increased leakage volume. It is also possible to notice that the variation of flow in pipes between the two scenarios is insignificant.

However, if we compare the case with a required pressure of one-meter with the case having a required pressure of 10m, a reduction in minimum leakage volume is observed. This is because, in these two cases the difference in flow in pipes is more significant than the network pressure difference caused by variation of the pump schedules. The pump schedule for the first case (1m) has only 4 hours OFF out of the 24 hours while the one with 10m required pressure shows the pump can be OFF for 7 hours of the day. This minimized frequency of pump ON status is responsible for the reduction in total leakage volume. The flow in the pipes is low with the case of the higher required pressure than the lower one leading to increased pressure but it is not significant enough to balance the lowering of pressure due to the pump pattern.

The energy consumed by the pumps is totally dependent on the optimal pumping pattern and this is clearly seen in Figure 23.

5.4 Pressure and Leakage comparison of existing operation and Optimal Operation Results

In order to examine how the optimization algorithm modifies the pump operation to minimize leakage, pressure graph contrast was made for three nodes representing three different situations that can trigger leakage. The first node is node wNode_971 and it represents the nodes exhibiting relatively high pressures in the network and which are also considered as potential leaking nodes. The second node is 1_20 which is from the set of critical nodes which experience relatively low pressure. The third node is node wNode_4063 which represents potential leaking nodes that connect pipes laying below external pressure from traffic load. The pressure in these three nodes are plotted as shown from Figure 24 to Figure 26.

Figure 24 displays the pressure variation between the custom and optimal operation at node wNode_971.

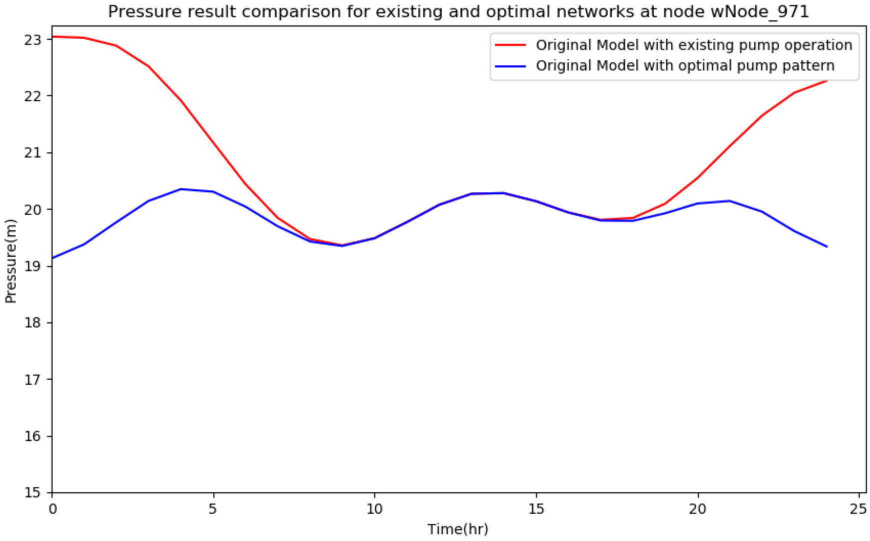


Figure 24 Pressure time graphs of existing and optimal operation at Node "wNodde_971"

It can be noted from Figure 24 that the optimal operation mainly adjusts the pressure during the night hours (starting from 19:00 to 06:00) especially during the midnight to the end of the third quarter of the night. The same situation is observed in the other two nodes as it can be seen from Figure 25 and Figure 26. The three figures show that during 00:00 to 03:00 there is considerable amount of pressure modification at the nodes in the network which reaches about 4m reduction in pressure.

Pressure modification by optimal operation at node 1_20 is shown in Figure 25.

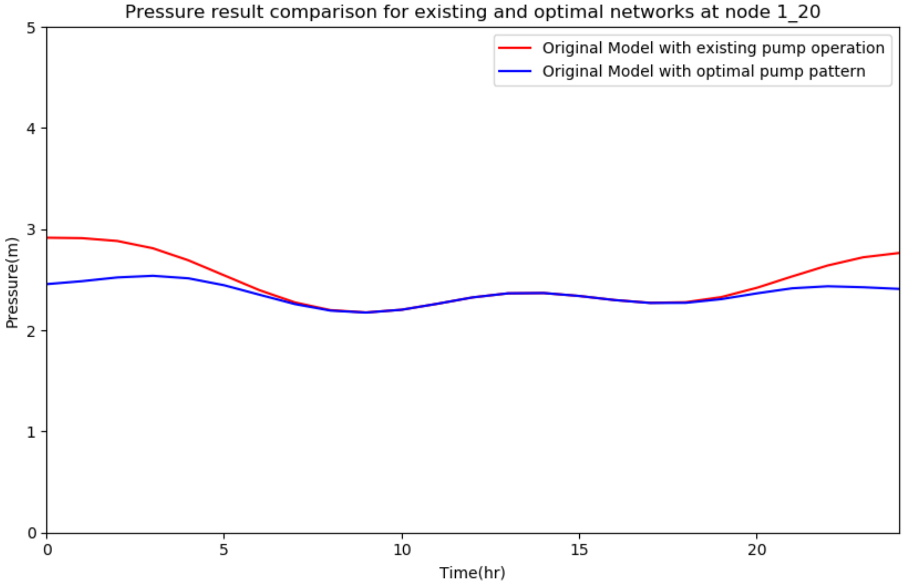


Figure 25 Pressure versus time graphs of Existing and Optimal Operation at Node "1_20"

The other selected node is “wNode_4063” and the resulting pressure is shown on Figure 26.

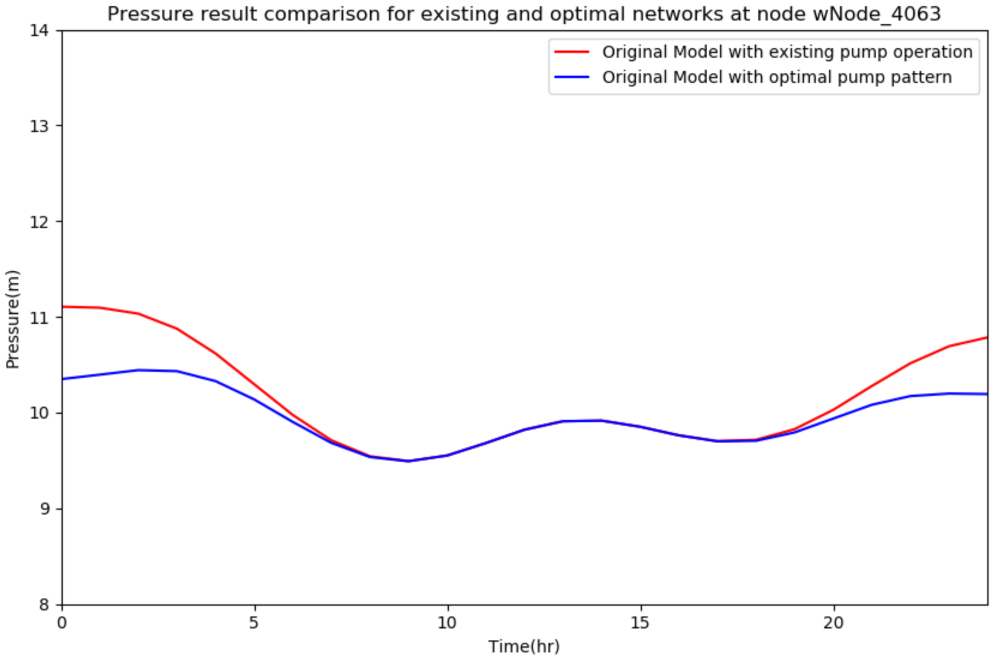


Figure 26 Pressure Comparison of existing and optimal operation at “wNode_4063”

It is also possible to observe that nodes experiencing relatively high pressure are the ones with major pressure adjustment. The nodes with low pressure go through only a little change with a maximum of 0.5m reduction in their pressure. This is because the constraint in the optimization is considers these critical nodes and will not allow much modification on those nodes so that the constraint would not be violated.

Figure 27 shows the leakage flow rate variation during the twenty-four hours at wNode_4063 under existing and optimal operations.

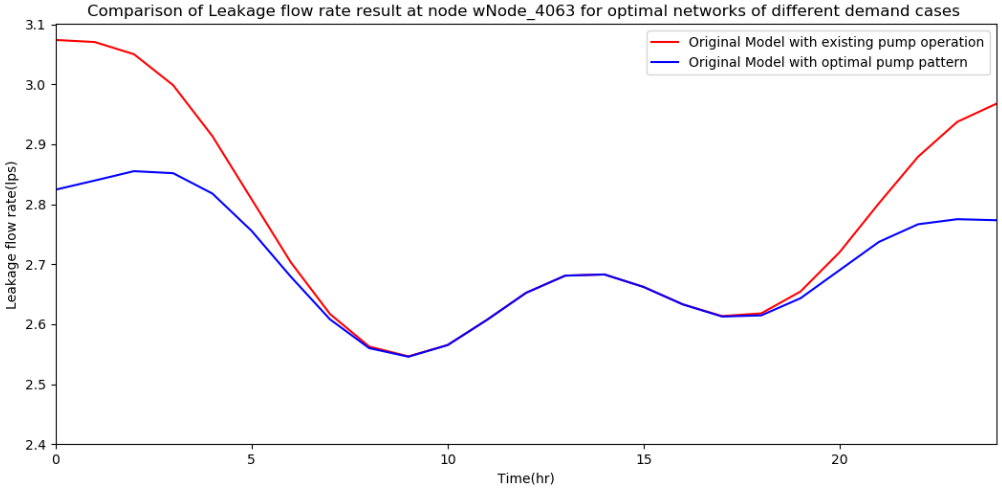


Figure 27 Leakage flow rate comparison of optimal and existing operations at wNode_4063

It can be seen from Figure 27 that the optimization algorithm minimizes the leakage rate mainly during the night time which is similar to what is seen with the pressure graphs and the pump schedules.

5.5 Pressure graph comparison of optimization experiment cases with networks of different required pressure and demand cases

The pressure result comparison for optimal networks with different required pressure cases at nodes wNode_971 and wNode_4063 is presented in Figure 28 and Figure 29.

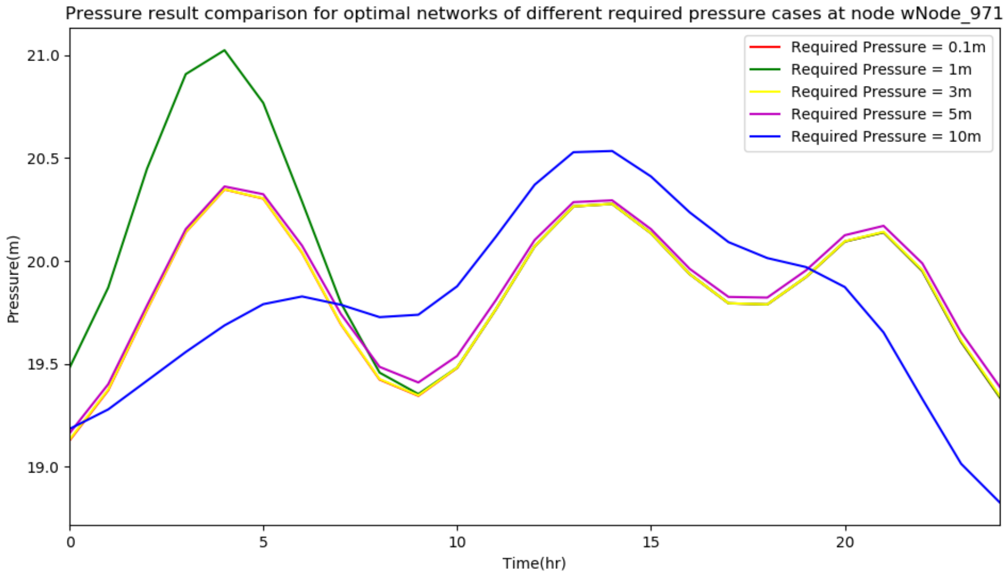


Figure 28 Pressure Comparison at Node wNode_971 for different required pressure cases

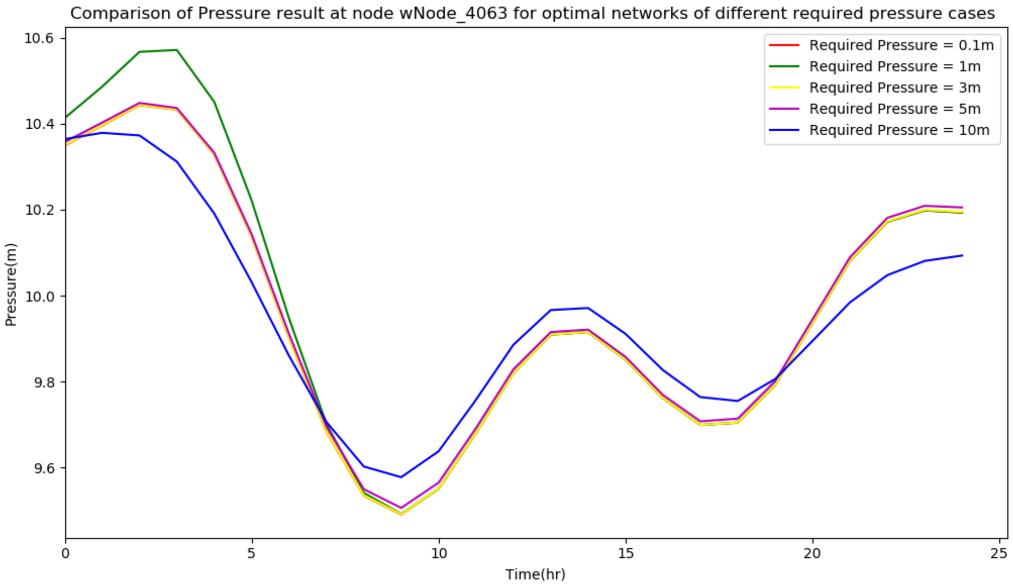


Figure 29 Pressure Comparison at Node wNode_4063 for different required pressure cases

Figure 28 and Figure 29show that when the required pressure is comparatively higher, the supplied demand gets lesser and hence the optimization algorithm finds opportunities to turn off the pump more frequently which reduces the pressure in the network especially of those nodes which experience higher pressure. And it can be said that the optimization algorithm focuses more on these nodes to minimize the leakage amount. This is seen with node wNode_4063, that, not much difference is perceived in the optimized pressure results of the network with different required pressure. It can also be perceived that the major time of the day where the optimization does the pressure minimization is between 00:00 and 06:00.

The other comparison made is between optimal networks of different demand cases at high pressure node (wNode_971) and another leaking node (wNode_4063) as presented in Figure 30 and Figure 31 respectively.

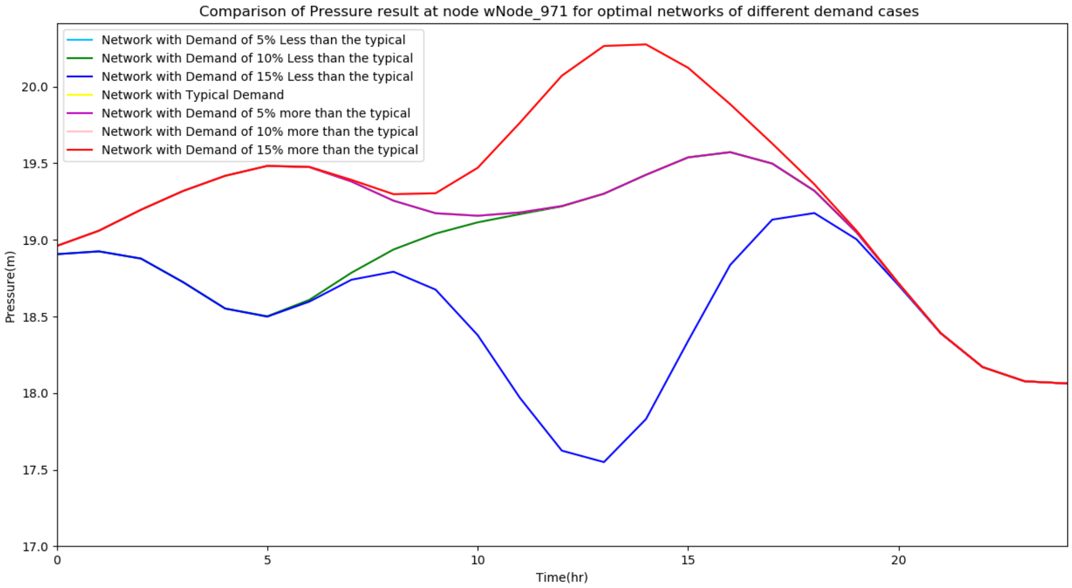


Figure 30 Pressure Comparison at node wNode_971 for different demand cases

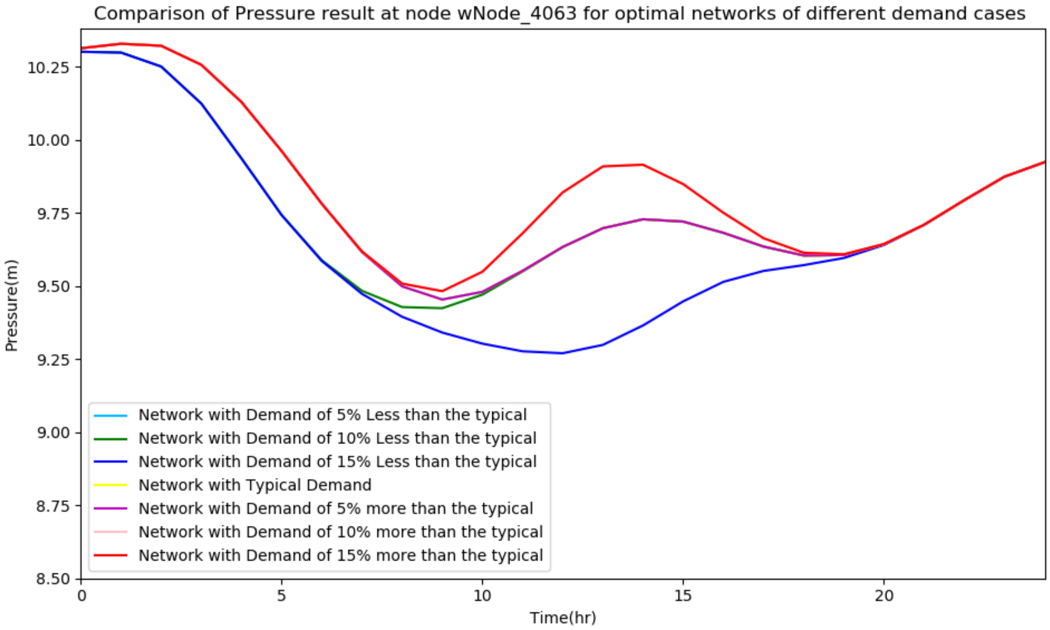


Figure 31 Pressure Comparison at node wNode_4063 for different demand cases

In both types of nodes, it is seen that the major variation in optimal pressure between different demand cases occurs during the midday. The reason behind this is that the optimal pump schedules of those cases which have less demand than the typical have one or more OFF statuses during midday in addition to the night time. Whereas, that of the cases with more demand than the typical show a continuously ON statuses during the day time especially during the midday.

Therefore, the nodal pressure during midday becomes higher for demand cases more than the typical than those cases with demand lower than the typical.

5.6 Real time Optimal Operation Framework

Figure 32 depicts the final model-based optimization framework suggested by this research to be followed in real-time pumping operation of the water distribution network.

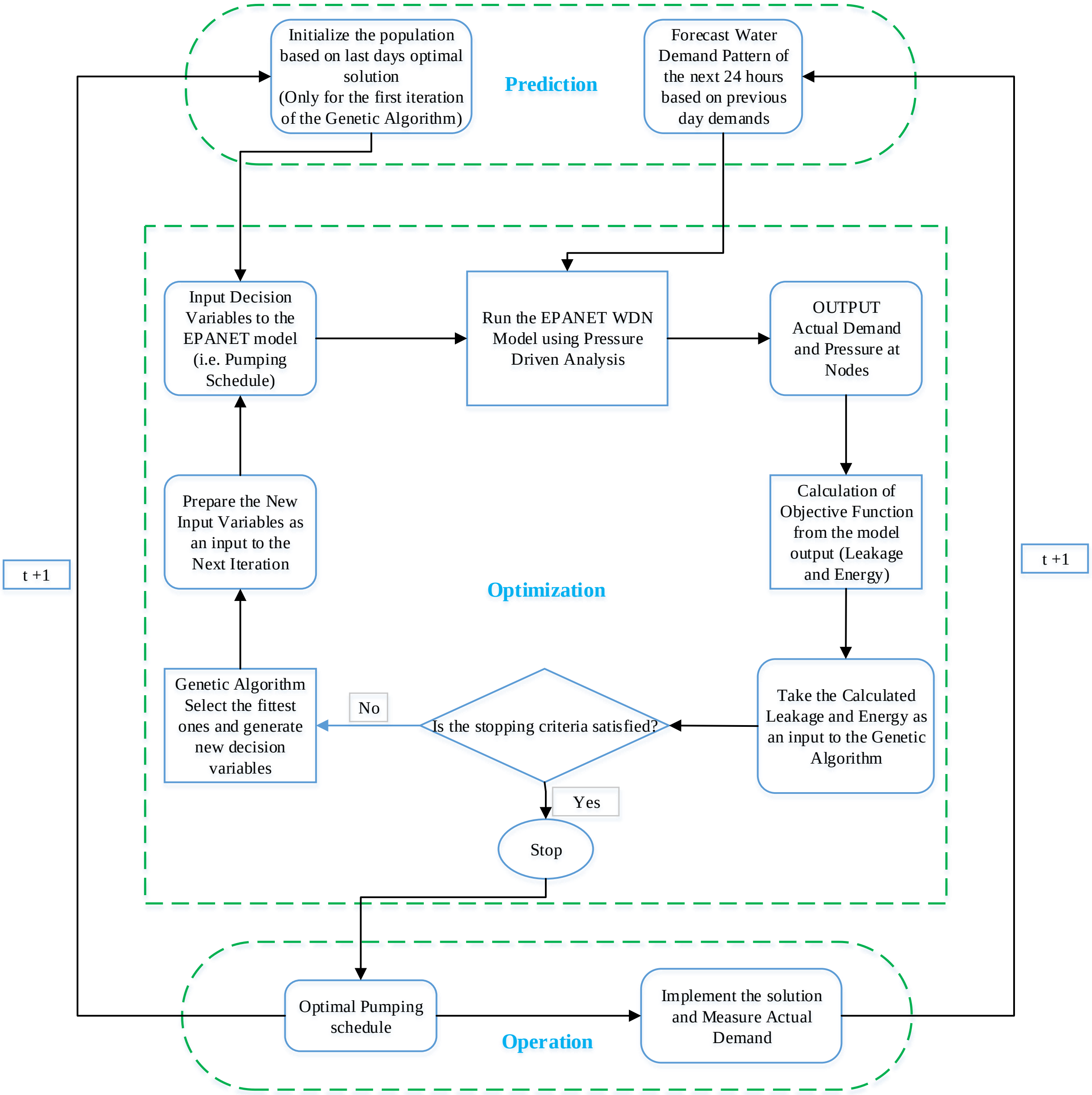


Figure 32 Real-time optimization framework

The framework is composed of three phases in a form of loop. The first phase is short term prediction of the water demand. Secondly, optimization of pump schedules will be done using genetic algorithms considering the predicted water demand. The last phase is implementation of the optimal solution, measurement of actual demand of the day and taking record of it. The current day optimal schedule can be used in the next day optimization solver genetic algorithm as initial population which makes the optimization run to save a significant time. The measured demand together with previous day measured demands can be used for prediction of the next day demand. This loop continues each day forming optimal operation framework.

The Autoregressive integrated moving average model (ARIMA (p, d, q) model is suggested by the author of this research to be used as a short term water demand forecasting method. It is well known method of forecasting for non-stationary time series data.

Chapter 6 Conclusion

6.1 Conclusion

Generally, it can be inferred from the research that it is possible to minimize leakage volume and energy consumption in water distribution systems which have pumps that directly feed the network. Unlike systems which pump towards a storage tank and feed the network with gravity, it is harder with systems that pump directly to the network to minimize leakage while satisfying service pressure using pump scheduling. Because, turning off pumps lead to violation of satisfying service pressure especially during peak demand hours. Nevertheless, this research showed that for the specific case of the Braila water distribution system, the leakage volume can be reduced by about 12% while the energy consumption can be minimized by 9%. In addition, it was observed that the optimization suggests schedules that minimize the network pressure principally during night time of the day (off peak hours) which helps to reduce the total leakage volume considerably.

Rule-based selection of potential leaking nodes can be an option to be used in leakage modelling and optimization of WDN operations where there is not enough capability to exactly spot the locations of leakage points. Traffic maps can assist to determine the pipes with external pressures. Diameter of pipes and measured pressure at pipes as well as historical reparation information help to filter the leaking pipes.

Modelling water distribution networks using pressure driven demand analysis helps to fill the gap shown in demand driven models. Especially when there is water deficit in the network to supply nodes with requested amount of demand due to scenarios such as where there is excessive amount of leakage in the pipes, pressure driven demand analysis better simulates the system.

It was also managed to see that in WDN models, in addition to consumption demand, leakage demand should also be incorporated as pressure dependent variable instead of demand dependent variable. This facilitates the optimization of WDN elements such as pumps operation in a way that they minimize leakage.

Last but not least, it has also been seen that water demand variation affects the optimal pump scheduling. And hence, short term water demand forecasting and real-time control should be taken into account for optimization and operation of pumps.

6.2 Limitations and Recommendation

1. In the last stages of the thesis research an important detail was communicated: that the pumps considered in the optimization are variable speed pumps (VSPs) instead of merely ON/OFF pumps, situation that was not included in their model. If it was known earlier, the optimization could also be tried with variable speed conditions which could give better results of minimized leakage and energy consumption and would allow to schedule two pumps (wLink_5805 andwLink_5806) instead of just one pump

(wLink_5805). However, as the python codes are now available, it is therefore recommended that further research is done to make this analysis.

2. Leakage modeling was done merely by using some rules that suggest where leaking nodes may occur and exact locations of leaking points are not known. Methods to predict the location of leaking nodes can be considered in further studies.
3. The model replication was done assuming that the original model was well-calibrated. However, it seems that the model has some issues regarding calibration. It would be better to calibrate the replicated model with real measured data which would increase the accuracy of the replicated model.
4. The demand forecasting method suggested in the real-time frame work can be studied better and or other methods of forecasting can be adopted based on further studies as this research did not go in detail about it.

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Appendices

Appendix A. - Research Ethics Declaration Form

Date: 29 March 2021
To: Ammanuel Bekele Tilahun
MSc Programme: WSE-HI
Approval Number: IHE-RECO 2020-096

Subject: Research Ethics approval

Dear Ammanuel Bekele Tilahun,

Based on your application for Ethical Approval, the Research Ethics Committee (RECO), IHE Delft RECO has been approved ethical clearance for your research proposal Optimising Pump Scheduling in Water Distribution Systems to Minimize Leakage. Case study: WDN of Braila, Romania.

This approval valid until April 16, 2021. You need to notify the RECO of any modifications to your research protocol. If you do not complete your research by the specified date, you should to contact RECO to request an extension.

Please keep this letter for your records and include a copy in the final version of MSc. Thesis, together with your personal reflection. Additional information is available at https://ecampusxl.un-ihe.org/course/view.php?id=1555&section=2.

On behalf of the Research Ethics Committee, I wish you success in the completion of your research.

Yours sincerely,

AMS

Dr. Angeles Mendoza Sammet
Acting Ethics Coordinator

Copy to: Archive.

Date: 2021-03-22

Subject: Personal Ethics Statement-

I Ammanuel Bekele, hereby confirm that I have followed the ethical procedures necessary for the research. The research considered people and the environment as it's aim is to save water and energy. I updated my knowledge of expertise to be able to do the research with a very good quality and to make the research completed successfully.

I have acknowledged the ideas or methods I took from other authors. The sources of data and any information used as an input for the research are mentioned. In addition, I have elaborated methods and procedures with enough detail so that later on anyone will be able to replicate the same procedure and validate the results. Besides, I have clearly indicated the limitations in the methods followed in the research. The results are thoroughly discussed why and how they appeared that way based on the physical science behind. The research was well reviewed by the research mentor and he is given the credit for his invaluable feedback in the acknowledgement part of this thesis. The report writing was given a good attention and it was made based on standard for academic writing, using good English.

Ammanuel Bekele
Author of this thesis

Appendix B. - Python Scripts

The Python scripts developed in this research are structured in three separate scripts. The first script is named as “wntr_obj_functions.py” which consists of functions that enable to modify the decision variable values and to calculate objective functions and constraints using the WNTR Python library. The second script is called “main_model_optimization.py” which runs the optimization using Platypus Python library, saves the results to a text file and plots the pareto optimal fronts. The third script, “leak_modelling_by_ratio.py” was used to replicate the original EPANET model by a new one that considers leakage flow as pressure-dependent variable. The second and third scripts are dependent on the first script. The three scripts are displayed on the next pages respectively.

wntr_obj_functions.py

```
# -*- coding: utf-8 -*-
"""
Created on Thu Dec 10 13:46:34 2020

@author: Ammanuel Bekele
"""

import wntr
#%%
def open_file (inp_file:str):
# Converts the input file to a wntr simulation object
    wn = wntr.network.WaterNetworkModel(inp_file)
    return wn
#%%
def plot_network(wn):
# Plots the network
    wntr.graphics.plot_network(wn, title=wn.name)
    return
#%%
def run_epanet_simulation(wn):
# Runs simulation object with PDD using EpanetSimulator and returns a
result file
    wn.options.hydraulic.demand_model = 'PDD'
    sim = wntr.sim.EpanetSimulator(wn)
    results = sim.run_sim(version = 2.2)
    return results
#%%
def actual_demand_series(results, node_id:str):
# Extracts Demand time Series of a node from a result file
    demand_series = results.node['demand'].loc[:,node_id] *1000
# in L/s
    return demand_series
#%%
def base_demand(wn, node_id:str):
# Extracts Base Demand value of a node in a wntr object
    junction = wn.get_node(node_id)
    base_dem = junction.demand_timeseries_list[0].base_value
    return base_dem * 1000
# in l/s
#%%
def pressure_series(results, node_id:str):
# Extracts Pressure time Series of a node from a result file
    pressure_seri = results.node['pressure'].loc[:,node_id]
    return pressure_seri
#%%
def pressure_at_time(results, node_id:str, at_time:int):
# Extracts Pressure value of a node at a specific time of the simulation
from a result file
    pressure = results.node['pressure'].loc[at_time*3600,node_id]
    return pressure
#%%
def pattern_values_list(wn, pattern_id:str):
# Returns the pattern values for an input of pattern name and wntr object
    pat = wn.get_pattern(pattern_id)
    return pat.multipliers
#%%
def modify_pattern(wn, pattern_id:str, new_pattern:list):
# Modifies pattern values with a new pattern
    pat = wn.get_pattern(pattern_id)
    for i in range(len(pat)):
```

```
        pat.multipliers[i] = new_pattern[i]
    return
#%%
def leakage_calc(wn, results, node_id:str, dem_pattern:str, t_step = 3600):
# Calculates nodal leakage volume (m3) at a junction having emitter for an
input of node_id and demand pattern and a result file
    junc = wn.get_node(node_id)
    coeff = junc.emitter_coefficient
    exponent = wn.options.hydraulic.emitter_exponent
    pressure_seri = pressure_series(results, node_id)

    if (pressure_seri > 0).all():
        leakage_flow_rate = coeff * pressure_seri**(exponent)
        average_leak_rate = sum(leakage_flow_rate)/len(leakage_flow_rate)
        nodal_leakage_volume = average_leak_rate * 24 * 3600
    else:
        nodal_leakage_volume = 0
    return nodal_leakage_volume                                  # in m3
#%%
def energy_consumption(wn,result,pump_id:str, t_step = 3600):
# Calculates Energy consumed by a pump (kWh) for an input of pump_id and a
result file
    pump_flowrate = result.link['flowrate'].loc[:,wn.pump_name_list]
    head = result.node['head']
    pump_energy_series = []
    for i in range(0,t_step*24,t_step):
        energy = wntr.metrics.pump_energy(pump_flowrate, head, wn).loc[i,
pump_id]/1000
        pump_energy_series.append(energy)
    pump_energy = sum(pump_energy_series)
    return pump_energy, pump_energy_series
#%%
def objective_func(file,new_pattern_values,pump_pat_id:list,
dem_pat_id:str,\
                       leaking_nodes:list, pump_id_list:list,
critical_nodes:list): # Calculates total leakage volume and Energy
consumption for an input of new pumping patterns list,list of leaking nodes
and list of pump_ids, list of critical nodes and demand pattern id
    wn = open_file(file)
    for i in range(len(pump_pat_id)):
        modify_pattern(wn,pump_pat_id[i],new_pattern_values[i])
    result = run_epanet_simulation(wn)
    total_leakage = 0
    for leaking_node in leaking_nodes:
        leakage = leakage_calc(wn, result, leaking_node, dem_pat_id)
        total_leakage += leakage
    total_energy = 0
    for pump in pump_id_list:
        energy = energy_consumption(wn,result,pump)[0]
        total_energy += energy

    P_at_cr_nodes = []
    for critical_node in critical_nodes:
        pr = min(pressure_series(result, critical_node))
        P_at_cr_nodes.append(pr)

    return total_leakage, total_energy, P_at_cr_nodes
#%%
```

main_model_optimization.py

```
# -*- coding: utf-8 -*-
"""
Created on Sat Jan 16 02:25:32 2021

@author: Ammanuel Bekele
"""
#%%
import time
import sys
sys.path.append('..\\Experiment')
from wntr_obj_functions import objective_func
import matplotlib.pyplot as plt
import numpy as np
from platypus import NSGAII, Problem, Binary, nondominated

start_time = time.time()

def Optimize_Pumping_schedule(x):


    file = r'D:\HI This
Year\Module_14_Thesis\Experiment\Braila_improved_with_emitters_6.inp'

    pump_pat_id = ['pat_wLink_5805']             # pump pattern ids

    new_pattern_values = [element for element in x]

    pumps_id = ['wLink_5805']               # List of Pumps to be optimized

    dem_pat_id = '3'                    # Demand Pattern

    leaking_nodes = ['1_11','wNode_4063',
'wNode_433','wNode_1759','wNode_417',\

'wNode_1915','wNode_1134','wNode_209','wNode_2032','wNode_1875',\
                         '1_20','1_90','wNode_1126','wNode_1807',\

'wNode_831','1_419','wNode_1470','wNode_650','wNode_2860',\

'wNode_636','wNode_971','wNode_3777','wNode_2360','wNode_932',\
                         'wNode_1','wNode_990','1_163','wNode_2116']

    Critical_nodes = ['1_20','1_37','1_48','1_90','wNode_1134',\
                      'wNode_3009','wNode_3012','wNode_4038','wNode_4048',\
                      'wNode_417','wNode_420','wNode_589','wNode_872',\
                      'wNode_948']  # Those nodes expected with large drop
in pressure

    min_P_req_at_cr_nodes = [1.5 for j in range(len(Critical_nodes))]
# Min Required pressure at critical nodes respectively

    Leakage = np.round(objective_func(file, new_pattern_values,
pump_pat_id, dem_pat_id, leaking_nodes , pumps_id, Critical_nodes)[0], 3)

    Energy = np.round(objective_func(file, new_pattern_values, pump_pat_id,
dem_pat_id, leaking_nodes , pumps_id, Critical_nodes)[1], 3)

    Pr_at_cr_nodes_at_cr_time = objective_func(file, new_pattern_values,
pump_pat_id, dem_pat_id, leaking_nodes , pumps_id, Critical_nodes)[2]
```

```
    return [Leakage, Energy] , [Pr_at_cr_nodes_at_cr_time[j] - 
min_P_req_at_cr_nodes[j] for j in range(len(Critical_nodes))]


problem = Problem(1, 2 , 14) # Number of dec. variables(Number of pumps to 
optimize), obj. functions and constraints respectively

problem.types[:] = Binary(24) # One pump pattern has 24 elements (on/off 
values during each hour of the day)
problem.constraints[:] = ">=0"
problem.function = Optimize_Pumping_schedule

algorithm = NSGAII(problem, population_size=50)
algorithm.run(3000)

nondominated_solutions = nondominated(algorithm.result)
print(nondominated_solutions)

end_time = time.time()
print("Time taken to finish the run= ",end_time - start_time,"s")
#%%
feasible_solutions = [s for s in algorithm.result if s.feasible]

## Save the result to a text file and display the results
with open("NonDominatedSolutions.txt","a") as report:
    for solution in nondominated_solutions:
        report.write(str(solution) + "\n")

with open("Report_file.txt","a") as report:
    for solution in algorithm.result:
        report.write(str(solution) + "\n")

plt.scatter([s.objectives[0] for s in nondominated_solutions],
            [s.objectives[1] for s in nondominated_solutions])


#plt.xlim([-1, 5])
#plt.ylim([0, 5])
plt.xlabel("Leakage(Cubic Meters)")
plt.ylabel("Energy(kWh)")
plt.title("Pareto fronts for 1 day simulation ")
plt.show()
#%%
```

leak_modelling_by_ratio.py

```
# -*- coding: utf-8 -*-
"""
Created on Sat Jan 30 17:16:37 2021

@author: Ammanuel Bekele
"""
import numpy as np
import pandas as pd
from wntr_obj_functions import pressure_series
from wntr_obj_functions import open_file
from wntr_obj_functions import run_epanet_simulation
file = r'D:\Module_14_Thesis\Experiment\ApaBraila15.02.2020-Base.inp'
Total_Leakage = 130     # In litres Per second
Exponent = 1.2
list_of_leaking_nodes = ['1_11','wNode_4063',
'wNode_433','wNode_1759','wNode_417',\

'wNode_1915','wNode_1134','wNode_209','wNode_2032','wNode_1875',\
                         '1_20','1_90','wNode_1126','wNode_1807',\

'wNode_831','1_419','wNode_1470','wNode_650','wNode_2860',\

'wNode_636','wNode_971','wNode_3777','wNode_2360','wNode_932',\
                         'wNode_1','wNode_990','1_163','wNode_2116']
wn = open_file(file)
result1 = run_epanet_simulation(wn)
# Calculate the Average Pressure At Each Leaking Node
average_pressure_list = []
for leak_node in list_of_leaking_nodes:
average_pressure_list.append(sum(pressure_series(result1,leak_node))/len(pr
essure_series(result1,leak_node)))

# Calculate the emitter coefficients for each leaking node based on the
available pressure at the nodes
ratio = [average_pressure_list[i]/sum(average_pressure_list) for i in
range(len(list_of_leaking_nodes))]
leak_demand = [np.round(j * Total_Leakage, 3) for j in ratio]
Coefficients =
[np.round(leak_demand[i]/((average_pressure_list[i])**Exponent), 3) for i
in range(len(list_of_leaking_nodes))]
frame = [list_of_leaking_nodes, average_pressure_list,
average_pressure_list, Coefficients]
df = pd.DataFrame(frame).T

#    Turn off the Loss demand from the original model
list_of_junctions = wn.junction_name_list
for i in range(len(list_of_junctions)):
    junction = wn.get_node(list_of_junctions[i])
    loss_demand = junction.demand_timeseries_list[0]
    loss_demand.base_value = 0

# Apply the Emitter Coefficients on the leaking Nodes
wn.options.hydraulic.emitter_exponent = Exponent
j=0
for junction_name in list_of_leaking_nodes:
    junction = wn.get_node(junction_name)
    junction.emitter_coefficient = (Coefficients[j])/1000
    j += 1
wn.write_inpfile('Braila_improved_with_emitters_6.inp')
```