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Optimal sequence of replacements in the renovation of water distribution networks

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Abstract

Water distribution networks (WDNs) are vital urban infrastructure. Aging components within WDNs pose a major concern due to their susceptibility to leakages. One possible strategy for addressing this issue -especially in severely degraded WDNs- is to replace a large part (up to 20%) of the conduit in the network (i.e., to perform a network renovation). However, the replacement of conduits presents challenges, especially in urban environments where construction must seamlessly integrate with city dynamics while minimizing disruptions to transportation infrastructure and water supply. Because of this, WDN renovation cannot be performed all at once, rather it requires a progressive and sequential replacement of conduits that can last months. Due to the nonlinear nature of the problem, it is expected that different sequences of conduits replacement will have different effects on the WDN dynamics. This study explores the existence of an optimal sequence of pipe replacement, that minimizes disturbances to users. The sequence is sought using the Probability-Based Incremental Learning (PBIL) algorithm. The obtained results underscore the significant impact of pipe replacement sequences on WDN dynamics. By strategically selecting pipe replacement sequences, cities can effectively manage their water distribution networks, mitigating the risks associated with aging infrastructure and minimizing disruptions to water supply.

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Chapter 1

Introduction

1.1 Introduction

Water distribution networks (WDNs) are a key type of infrastructure that is deeply connected to the urban fabric. The primary goal of a distribution system is to provide consumers with safe water at appropriate pressure levels and in adequate quantities, ensuring continuous service and maximum coverage at a reasonable cost. To achieve this aim, organizations must develop operational procedures that enable the system to function efficiently, consistently, and cost-effectively. [5] WDNs are made up of heavy equipment and components are installed underground (usually below busy roads), and are therefore very difficult to maintain and monitor.

Leakages in water supply systems and urban water distribution networks are influenced by a myriad of factors, necessitating a comprehensive understanding and approach to effectively address this critical issue. Leakage may manifest in diverse elements of the distribution system, such as transmission pipes, distribution pipes, service connection pipes, joints, valves, and fire hydrants [11].

The aging of Water Distribution Networks (WDNs) globally, coupled with insufficient maintenance practices, poses a significant challenge. As WDN components age, they become increasingly susceptible to failure, leading to a higher incidence of leaks throughout the network over time. These leaks represent a substantial problem for WDN management, with ramifications extending beyond infrastructure integrity. Notably, leaks contribute to a reduction in the availability of water resources, a critical concern in regions grappling with water scarcity. However, even in countries where water resources are abundant, leakages remain a pressing issue. One of the primary concerns stems from the economic consequences associated with leaks. Economic damage incurred due to leakages encompasses various facets, including the cost of wasted water, expenses associated with repairs, and potential losses in revenue for water utilities. Furthermore, the indirect costs of leakages, such as damage to property and infrastructure, further exacerbate the economic burden. As such, addressing leakages in WDNs is imperative for both resource conservation and economic sustainability, underscoring the urgent need for proactive management strategies and investment in infrastructure maintenance and renewal.

External disturbances, such as construction activities or accidental damage, pose additional risks to the network's structural integrity, highlighting the need for robust protective measures. Poor construction practices and errors during installation can introduce weaknesses in the system, making it more susceptible to leaks and underscoring the importance of adherence to quality standards. Ground movement, whether due to geological factors or soil shifting, can compromise pipeline integrity over time, necessitating ongoing monitoring and maintenance efforts. Water quality issues, including corrosive water or chemical reactions with pipeline materials, can accelerate degradation and exacerbate leakage problems, necessitating careful management of water chemistry. Temperature variations may also play a role, causing materials to expand and contract, potentially compromising their integrity and highlighting the importance of accounting for environmental factors in infrastructure design. Finally, design flaws, such as sub optimal layout or sizing of the distribution network, can exacerbate leakage issues by creating weak points in the system, underscoring the importance of meticulous planning and engineering expertise in infrastructure development. Addressing these factors comprehensively is essential for effectively mitigating leaks and maintaining the reliability of water supply systems, safeguarding vital resources and ensuring sustainable infrastructure for future generations. [19]

In many developing countries, water utilities face a significant challenge known as "non-revenue water" (NRW), which refers to the disparity between the water supplied to the distribution system and the amount billed to consumers. This issue stems from substantial water loss due to leaks. High levels of NRW not only result in financial losses for water utilities but also lead to increased operational costs.

Estimates suggest that the annual global losses due to NRW exceed US$14 billion, with more than a third of these losses occurring in developing countries. [13].
On the other hand, Water often needs to undergo purification and pumping.These operations are costly, and so leaking water means leaking money. In a study on energy losses in Brazil, it was revealed that leakages account for 0.64% of the total energy produced, with a higher impact of 1.12% on hydro-power energy alone, which is significant given that hydro-power is the primary source of electricity in Brazil. Furthermore, a more detailed investigation in this study focused on a system utilizing a reservoir for both energy generation and water supply. Findings indicated that leakages not only affect energy consumption in pumping stations but also diminish the water stored in the reservoir. Consequently, hydro-power production declines, potentially resulting in negative net energy during dry periods, necessitating the import of energy from other power plants to maintain water supply [21].
In addition to the considerable challenges posed by water leakages, it's essential to recognize their potential cascading effects within water supply networks. Beyond the physical loss of water, leakages can also trigger a decrease in network pressure, a critical parameter in ensuring effective water distribution. This decline in pressure can have far-reaching consequences, extending beyond infrastructure concerns to directly impact end-users. For instance, reduced pressure may result in inadequate water flow to households and businesses, leading to customer dissatisfaction and frustration. Moreover, in cases where water utilities have contractual obligations to maintain minimum supply specifications, such as guaranteed water pressure levels outlined in agreements with consumers, leak-induced pressure reductions can result in noncompliance issues. This not only jeopardizes the trust and satisfaction of customers but also places water utilities at risk of legal or regulatory repercussions. Therefore, addressing leakages goes beyond mere conservation efforts; it is a crucial step in upholding the reliability, efficiency, and regulatory compliance of water supply systems. Beyond the immediate loss of water from the distribution network, the infiltration of leaks into the surrounding soil introduces a myriad of challenges for water management authorities. This infiltration process can manifest in various ways, including the unintended entry of leaked water into sewer systems, thereby exacerbating the complexities associated with wastewater management. In such instances, the volume of wastewater requiring treatment at sewage plants experiences

an unforeseen increment, straining the capacity and efficiency of treatment facilities. Moreover, the ingress of leaked water into sewer networks poses additional risks, including the potential for underground erosion pathways to form. This phenomenon not only compromises the stability and integrity of underground soil structures but also poses a risk of undermining the structural integrity of adjacent infrastructure. Consequently, the management of leakages transcends mere conservation efforts, necessitating a comprehensive approach that addresses the multifaceted challenges posed by infiltrated water.

To reduce leakages, a number of strategies have been adopted. Strategies span from the management of pressure in the network, the creation of districts, and the research of the main leakage's location for localized intervention in damaged pipes. Bosco et al. [2020] [3] conducted a simulation analysis to evaluate the effectiveness of rehabilitation measures and active pressure control strategies in reducing water leakage within a southern Italian water distribution network (WDN). Three scenarios were examined: pipe rehabilitation, local pressure control, and remote real-time pressure control. Pipe rehabilitation significantly reduced water leakage compared to the current operational scenario. Additionally, local pressure control further improved leakage reduction, while remote real-time pressure control offered additional benefits, especially when water demands vary significantly over time and across different locations.

The classic approach of replacing old pipes en masse to address leakage in water supply systems may seem straightforward but falls short of the most effective solution. A more optimal approach involves accurately identifying and repairing the specific sources of leakage. This is achieved through a systematic process, where the entire network is divided into District Meter Areas (DMAs), each supplied by a single pipe equipped with a flow meter. This setup enables immediate detection of leaks and pinpointing their locations within the network.

Alvisi (2015) [1] introduces a novel procedure for the optimal design of District Metered Areas (DMAs) in water distribution networks. The procedure employs a multilevel balancing and refinement algorithm to partition the network and determine optimal meter positions. Unlike existing methods relying on graph partitioning techniques, this approach simultaneously addresses the partitioning of nodes into districts and the selection of pipes to leave open or close. Application of the procedure to a real-world network demonstrates its superior performance compared to other approaches reported in the literature. The proposed procedure adjusts node allocation based on the available metering points and the configuration of open and closed pipes between DMAs, leading to more efficient partitioning solutions. Overall, the study underscores the effectiveness of the proposed procedure for optimizing DMA design in water distribution networks.

In a study by Bui et al.[2020] [4] , authors presented a comprehensive review of water network partitioning (WNP) techniques, focusing on the division of water distribution networks into District Metered Areas (DMAs) to enhance operation and management efficiency. The review covered two main phases: clustering and sectorization. Clustering algorithms, such as graph theory-based methods and multi-agent approaches, were examined for defining optimal DMA configurations considering hydraulic performance, network topology, reliability, water quality, and cost-benefit ratio. Sectorization involved physically segmenting the network with gate valves and flow meters placement optimization to minimize negative impacts on hydraulic performance, energy use, leakage, and cost. The study underscored the significance of innovations in clustering algorithms and sectorization optimization for WNP.

Broken pressurized pipes emit detectable noise, which can be precisely located using specialized acoustic instruments. By isolating DMAs during nighttime step tests, it becomes possible to identify the most leak-prone pipes swiftly, facilitating rapid leak recovery and minimizing water loss. [17]

Karathanasia and Papageorgakopoulos [2016] [12], discussed the development of a leakage control system for the water supply network in Patras, Greece, by the Municipal Enterprise of Water Supply & Sewerage network of Patras (DEYAP). The study highlights the city's significant leakage issues, with approximately 55% non-revenue water in the system. DEYAP aimed to implement a permanent Leakage Control System based on the International Water Association (IWA) methodology, which includes establishing District Metered Areas (DMAs), pressure management, GIS-based decision support systems, database aggregation, procurement of leak detection equipment, and personnel training. The authors emphasize the high physical losses in the network and stress the importance of DMAs and pressure management in reducing real water losses. DEYAP plans to establish operational procedures for efficient network management, such as analyzing minimum night flow, reviewing flow measurements, pressure management, and evaluating overall

network performance for further improvements.
The process of addressing leakages in Water Distribution Networks (WDNs) is a multifaceted and critical endeavor, often referred to as "renovation." Renovation efforts are essential for enhancing the integrity and efficiency of aging infrastructure, as well as for mitigating the pervasive issue of leakages that plague many water networks worldwide. These efforts require comprehensive strategies aimed at overhauling deteriorating components within the network, involving various stages and approaches to ensure effectiveness. At the core of renovation works lies the proactive replacement of conduits, which serve as the arteries of the water distribution system. These conduits, over time, can suffer from wear and tear, corrosion, and other forms of degradation, leading to leaks and inefficiencies in the network's operation. To address this, renovation initiatives often entail the systematic replacement or rehabilitation of these conduits, utilizing advanced materials and construction techniques to enhance their longevity and performance. Furthermore, renovation projects often involve collaboration between various stakeholders, including water utilities, government agencies, engineering firms, and the local community. This collaborative approach ensures that renovation efforts are aligned with broader goals such as sustainability, resilience, and cost-effectiveness, while also fostering transparency and accountability in the decision-making process.
The rationale behind such extensive replacement lies in the recognition of the profound impact that aging infrastructure has on leak prevalence and overall network performance. By strategically replacing outdated conduits, water utilities can effectively address vulnerabilities and bolster the resilience of the network against future deterioration. Moreover, the comprehensive nature of renovation works enables utilities to modernize infrastructure in alignment with evolving standards and technological advancements.
In recent years, there has been a notable proliferation of renovation investments geared towards revitalizing WDNs and fortifying their operational efficiency. This trend underscores a paradigm shift towards proactive asset management and sustainability driven infrastructure development. By prioritizing renovation initiatives that prioritize leakage reduction, water utilities can not only safeguard precious water resources but also mitigate economic losses associated with wastage and inefficiency. Furthermore, the widespread adoption of renovation investments signifies a concerted effort to future-proof water infrastructure and mitigate the risks posed

by aging networks. By embracing innovative approaches to renovation and infrastructure renewal, utilities can navigate the complex challenges posed by aging infrastructure while advancing towards a more sustainable and resilient water management paradigm. As such, renovation emerges as a cornerstone of proactive asset management, ensuring the longevity and reliability of water distribution systems in an era of evolving environmental and operational demands.

The replacement of conduits within Water Distribution Networks (WDNs) presents unique challenges, particularly in urban settings where minimizing disruption to daily life is paramount. Integrating worksites for conduit replacement into the urban dynamics requires careful planning and coordination to ensure that transportation infrastructures remain functional and disruptions are kept to a minimum. Additionally, maintaining uninterrupted water supply to users during pipe replacement works is essential, with total outages of water supply limited to sporadic occurrences lasting only a few hours per day.

These stringent requirements dictate that WDN renovation must be carried out through a progressive, or sequential, replacement of conduits. This approach involves tackling a limited number of conduits at a time, allowing for focused and efficient work while minimizing disruptions to the surrounding area. By strategically scheduling replacements and coordinating with local authorities, utilities can ensure that the impact on traffic flow and accessibility is minimized, and that water users experience minimal inconvenience.

Furthermore, the sequential replacement approach enables utilities to prioritize conduits based on factors such as age, condition, and criticality, ensuring that resources are allocated effectively to areas most in need of renovation. Additionally, it allows for the implementation of innovative construction techniques and technologies that further streamline the replacement process, such as trenchless methods that minimize excavation and reduce the time required for restoration.

In their study on pipe replacement strategies in water supply networks, Van Dijk and Hendrix (2016) [22] investigate the economic implications of coordinated versus uncoordinated replacement. Their research reveals that coordinated replacement, defined as the strategic alignment of pipe replacement activities with planned road work by other operators of underground infrastructure, yields significant economic benefits, particularly in scenarios with larger budgets. With a higher budget, coordinated replacement results in a greater number of pipe replacements at a lower total replacement cost, albeit with higher expected failure costs. Conversely, uncoordinated replacement may incur higher total expected failure costs due to potential inefficiencies in timing pipe replacements. Furthermore, the study highlights the importance of considering planned road work by other infrastructure operators, as coordinating pipe replacement with scheduled road work can substantially reduce replacement costs, leading to considerable savings over a planning period. These findings provide valuable insights for decision-makers in water supply network management, emphasizing the economic advantages of coordinating replacement activities with scheduled road work.

The paper by Nafi and Kleiner (2010) [15] presents an innovative approach for optimizing the scheduling of individual water mains for replacement within a predefined planning period. Focusing on the low-level scheduling aspect, the study integrates considerations such as budgetary constraints, adjacency of infrastructure works, and economies of scale into the replacement decision-making process. Utilizing a multiobjective genetic algorithm scheme, the proposed approach efficiently explores the vast solution space of pipe replacement schedules. By addressing practical issues like harmonization with other infrastructure works and economies of scale, the study contributes to enhancing the efficiency and effectiveness of water main replacement strategies. The research builds upon previous efforts in the field, offering a comprehensive review of relevant literature and highlighting the significance of considering individual water mains in replacement planning. Moreover, the paper discusses potential future directions for incorporating additional factors, such as hydraulic performance and network reliability, into the optimization framework.

Ghobadi, Jeong, and Kang (2021) [8] introduce an innovative strategy for the systematic scheduling of water pipe replacements within large-scale water distribution networks (WDNs), addressing the pressing challenges posed by aging infrastructure and budgetary constraints. Given the critical role of WDNs in providing potable water to urban communities, the authors emphasize the need for careful management to ensure the network's integrity and reliability. Their proposed approach leverages life cycle cost (LCC) assessment and optimization algorithms to develop an optimal replacement schedule that aligns with annual budget limitations. By simultaneously minimizing the imposed LCC on the network, reducing the standard deviation of annual investment, and minimizing the average age of the network, the framework aims to smooth the investment time series, thus facilitating more efficient resource allocation over time. Through the utilization of multi-objective optimization techniques, the authors provide water infrastructure managers with a practical tool to balance the competing demands of infrastructure maintenance and financial constraints, ultimately enhancing the sustainability and resilience of WDNs. This comprehensive approach represents a significant advancement in infrastructure management, offering a tailored solution to the complex challenges faced by water utilities worldwide.

The scope of this study is intricately tied to the hydraulic effects of renovation within WDNs. These effects encapsulate a myriad of factors, including pressure dynamics, flow velocity, leakages, power consumption, and demand deficit, all of which play pivotal roles in the network's performance and user satisfaction. By focusing exclusively on hydraulic considerations, the study aims to provide a comprehensive understanding of how renovation activities influence the intricate dynamics of WDNs.

It is essential to recognize that the hydraulic effects of renovation are deeply intertwined with the broader dynamics of urban infrastructure and societal needs. While traffic issues and other external factors are excluded from the study's scope, their interplay with hydraulic considerations cannot be entirely disregarded. As such, future research endeavors may seek to explore the holistic impact of renovation activities, encompassing both hydraulic and non-hydraulic facets, to provide a more nuanced understanding of WDN renovation's implications.

Delving deeper into the intricacies of sequential replacement, it becomes evident that the nonlinear nature of the problem poses significant challenges. The order in which conduits are replaced can have profound implications for both users and the WDN's overall dynamics. For instance, the temporary disconnection of water mains serving specific buildings during replacement activities can disrupt daily routines and necessitate contingency measures to mitigate inconveniences.

Furthermore, alterations in hydraulic characteristics following conduit replacement can reverberate throughout the network, affecting pressure dynamics and leakage rates in unforeseen ways. These ripple effects underscore the importance of strategic planning and meticulous analysis in optimizing the sequence of replacement to minimize disruptions and maximize the efficiency of renovation efforts.

At the end, the sequential replacement of conduits during WDN renovation represents a multifaceted challenge that extends beyond mere infrastructure upgrades. By focusing on the hydraulic effects of renovation, this study aims to shed light on the intricate interplay between renovation activities and the dynamics of urban water systems.
In this study, the exploration delves deep into the intricate realm of water distribution network renovation, posing a fundamental query: Is there an optimal sequence of replacements that can effectively revamp these networks while minimizing detrimental effects on both end-users and the network's operational dynamics? The crux of the matter lies in discerning what constitutes "optimal" in this context an optimal sequence entails a meticulously planned series of replacements aimed at alleviating adverse impacts such as reduced pressure or demand shortages experienced by consumers, while also addressing inherent network challenges like leakages and energy consumption fluctuations. To unravel this complex conundrum, a multifaceted approach is essential. Firstly, it necessitates a thorough assessment of the hydraulic repercussions associated with various replacement scenarios, encompassing factors such as fluctuating pressure dynamics at junction points and flow rates along conduits over extended periods. Secondly, the study endeavors to quantify these adverse effects through a scalar measure, facilitating a systematic comparison of disparate replacement sequences to pinpoint the most efficacious solution. Finally, the ultimate goal is to identify and implement a meticulously tailored sequence of replacements that not only optimizes network performance but also minimizes disruptions and inconveniences for end-users. While optimization methodologies akin to this have historically found application in fields like transportation engineering (particularly in projects entailing the phased implementation of infrastructure enhancements like bus lanes) by Murat Bayrak et al. [2021] [2], this study pioneers the adaptation and application of such methodologies to the intricate domain of water distribution network rehabilitation. Through this pioneering endeavor, the study aims not only to offer invaluable insights into optimizing urban water system's efficiency and resilience but also to pave the way for transformative strategies that can revolutionize the landscape of water infrastructure management.

Chapter 2

System considered and formulation of the problem

The renovation of a WDN is performed with the progressive replacement of a selected number of conduits. This sequential replacement entails a well-defined sequence of many different single operations. Examples of single operations are:

(i) Disconnection from the network of an old pipe;

(ii) Opening/closing of valves;

(iii) Putting into service of a new pipe.

These operations may affect the hydraulics of the system and key characteristics such as the topology of the network, the water demands at junctions, and the conduit's resistance may be modified during these operations.
For instance, during pipe replacement endeavors, governing bodies may opt to alter the network topology within specific zones and utilize varying pipe diameters and materials compared to the original configuration. Moreover, transitioning from old to new pipes alters the roughness characteristics.
The modification of these key characteristics may have in turn an effect on the hydraulic behavior of the WDN itself, that is described by the time series of flow in links, and pressure and water outflow (demand) at junctions.

One additional characteristic of renovation works is that single operations require some time to be implemented, and so they begin and end at different time, and therefore can interact with other time-variations of WDNs (e.g., the variation of demand over the day, tanks dynamics). Each water distribution network (WDN) exhibits distinct daily, weekly, monthly, and seasonal demand patterns, necessitating consideration during pipe replacement phases. The timing of pipe disconnections should be meticulously determined in accordance with these temporal patterns and expert advice from authorities.

In this context, the aim of this work is to find the "optimal sequence" of the operations to be implemented. The focus is therefore on the time that spans from the beginning of the works of renovation (at the calendar time $t = t_0$) up to the end of these works, that occurs at the calendar time $t = t_0 + T_W$.
As stated before, modifications of the network can induce unwanted effects (e.g., pressure reductions that cause user's dissatisfaction or technical problems). The disconnection of a pipe can result in a temporary drop in pressure at nodes adjacent to the disconnected pipe. This decrease in pressure during the disconnection period may lead to user dissatisfaction. Additionally, the reduced pressure in the pipes can cause a corresponding decrease in water usage by users from the intended levels.

In order to quantify such negative effects, the focus will be on the analysis of quantitative data such as the time-series of pressure and flow over the period $[t_0, t_0+T_w]$. In the following, it will be shown that possible adversities registered in the time-series of pressure, demand, and flow can be aggregated to scalars that quantify the "cost" of the operations of network replacement.
In this way, the problem of minimizing disturbances during network renovation becomes a problem of cost minimization. Minimization of costs is an issue well addressed in the literature, that reports powerful and efficient numerical tools.

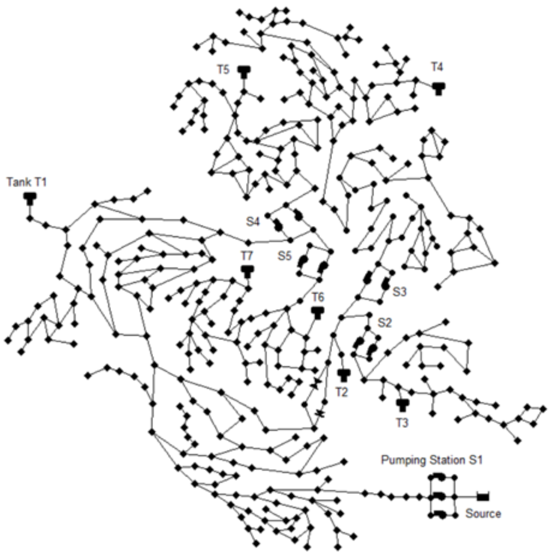
Two key issues render this particular optimization problem of interest:

- The first issue is that the objective of the optimization is not one particular status of the network (i.e., a static configuration). Rather, the objective is the sequences of operations to be implemented to go from one particular status of the network (current status) to another particular status of the network (design configuration). This makes the objective of the optimization a dynamic sequence.

- The second issue is that different perspectives affect how the cost is evaluated from the time-series of pressure, demand, and flow. For example, one first perspective (of the Water Utility) is to keep the pressure in the network above the minimum value that must be guaranteed (according to the contracts with customers). In accordance with the network's topography, elevation of junctions, and adherence to national standards, each network establishes a minimum pressure threshold that must be met. Failure to satisfy this minimum pressure criterion may result in user dissatisfaction.One other perspective (of users) is to get as much water as is needed. The reduction in water usage during pipe disconnection periods at certain junctions within the network leads to decreased revenue for the water provider company.

2.1 Components of the network

The first step to solve the aforementioned optimization problem is to model how the hydraulic behavior of the considered WDN evolves operation after operation. To do that, we focus on a generic WDN, made up of links (pipes, pumps, valves) that connect junctions (users, reservoirs, tanks). The following discussion pertains to the cartographic representation of C-Town's water distribution network, herein referred to as the C-Town map. Its schematic depiction and symbolic components are presented below:



(a) C-Town network

Component	Symbol
Junction	●
Conduit	●—●
Pump	●—pump—●
Valve	●—⋈—●
Reservoir	reservoir symbol
Tank	tank symbol

(b) Components

Figure 2.1: Overall Caption

In the following the components of the network would be discussed:

2.1.1 Links

Links (conduits, pumps, and valves) are identified by the index i. N_c conduits are installed in the WDN. The hydraulic resistance depends on the length L_i, the diameterD_i, and on the equivalent roughness ϵ_i (according to the Colebrook-White's approach).

In pipes the flow velocity is V_i and the flow rate is Q_i. Along the i-th pipe, distributed leakages occur. Leakages depend on the diameter, age of the material of the pipe, and on the pressure. The leakage per unit length is $q_{L,i} = C_{L,i} \cdot [P_i(x_i)]^{0.5}$, where $P_i(x_i)$is the pressure at the location x_i in the i-th pipe, whereas $C_{L,i}$ is a leakage coefficient that takes into account the diameter, age, material and condition of the conduit.

2.1.2 Pumps

Pumps are characterized by the pump-curves $C_{P,i}$ $(\Delta H_{P,i}, Q_{P,i})$, where $\Delta H_{P,i}$ is the total head and $Q_{P,i}$ is the flow rate. N_P pumps are installed in the WDN.The (constant) efficiency of pumps is η_i, whereas the cost of energy is c_E. Pumps are dynamic elements that can be switched on/off by controls, so the additional variable $s_{P,i}$ is defined to monitor the status of the machine.

2.1.3 Valves

For what concerns valves, here we only consider throttle control valves with head loss coefficient $C_{V,i}$ that satisfies the equation $\Delta H_{V,i} = C_{V,i} \left[\frac{2Q_{V,i}}{g\pi D_{V,i}^2} \right]^2$ where $Q_{V,i}$ is the flow through valve, $\Delta H_{V,i}$ is the head drop across the valve, and $D_{V,i}$ is the nominal diameter of the valve. N_V valves are installed in the WDN. Similar to pumps, valves are dynamic elements that can be switched on/off by controls, so the additional variable $s_{V,i}$ (that monitors the status of the valve) is defined.

2.1.4 Junctions

Junctions are identified by the index j which N_j junctions are installed in the WDN. Junctions are characterized by the user's demand $Q_{D,j}$, by the leakage $Q_{L,j}$, and by the elevation z_j. Users require the time-varying demand $Q_{DU,j}(t)$, but the actual outflow that can be provided by the WDN is constrained by pressure. In particular, the parameter $P_{\min,j}$ is the minimum pressure at the j-junction so that the outflow provided by the network can be equal or larger than the demand required by users. On the other hand, P_j is the (possibly time-varying) pressure at the j-junction. Two cases can be considered:

- When $P_j \geq P_{\min,j}$, the outflow from the j-junction is $Q_{D,j} = Q_{DU,j}(t)$ (i.e., the user's demand is fully satisfied).
- When $P_j < P_{\min,j}$, the outflow is $Q_{D,j} < Q_{DU,j}(t)$. The user's demand cannot be fully satisfied, and a demand deficit is $\Delta Q_j(t) = Q_{DU,j}(t) - Q_{D,j}(t)$ arises.

It should be finally remarked that the time-varying demand can be written as $Q_{DU,j}(t) = \bar{Q}_{DU,j}\Pi_j(t)$, where $\bar{Q}_{DU,j}$ is the (usually daily-) average demand, whereas

$\Pi_j(t)$ is a time pattern that describes the temporal variations. In this study, time variations are limited to a weekly typical pattern with hourly time-steps.

2.1.5 Tanks

Tanks are identified by the index τ and N_τ tanks are installed in the WDN. Tanks are characterized by the level $H_{T,\tau}(t)$, maximum level $H_{\max,\tau}$, minimum level $H_{\min,\tau}$, elevation of bottom $z_{T,\tau}$, and by the radius $R_{T,\tau}$. Similar to pumps and valves, tanks are dynamic elements, and to fully describe a hydraulic problem it is necessary to know the tank's initial level $H_{0,\tau}$.

2.1.6 Reservoirs

Reservoirs are identified by the index r. N_R reservoirs are installed in the WDN, and are characterized by the head $H_{R,r}$.

2.1.7 Controls

Additional (intangible) elements that deeply affect the dynamics of a WDN are controls. Controls are a set of logical rules that modify the status of valves and pumps according to a set of state variables. State variables can be:

- The pressure in prescribed nodes
- The level of tanks
- The time of the day
- The flow rate in some prescribed link

2.2 Economic and Compliance aspects of WDN

For the purpose of this study, it necessary to consider two more aspects, to fully characterize a WDN.

Cost of water

The first aspect is the economics of water production and distribution. The key parameters to be considered are:

- The cost sustained by the Water Utility to produce a volume of water, namely $c_{W,\text{prod}}$
- The price the Water Utility bills water to customers, namely $c_{W,\text{bill}}$.

Compliances of the system

The second aspect concerns the compliance of the service provided by the Water Utility with the contracts signed between the Water Utility and customers. The key parameter in this case is the minimum pressure that the Water Utility should guarantee to customers, namely P_{cmp}.

Chapter 3

Modelling

3.1 Introduction to Modelling

Water distribution networks (WDNs) are complex systems of pipes, pumps, valves, and storage tanks that deliver potable water to consumers. Hydraulic modeling plays a crucial role in analyzing, designing, and managing these networks efficiently. Hydraulic modeling involves the use of mathematical equations and computational tools to simulate the flow of water through the network under various operating conditions. In below first the principles of hydraulic modelling would be discussed then the software used in this study for hydraulic modelling would be introduced.

3.2 Hydraulic principles of modelling

To model the hydraulic system following equations can be used:

1. Equation of head losses along the pipes and in junctions
2. Mass Continuity formulas at junctions
3. Boundary conditions of the network (reservoir)

In the following the corresponding equations would be explained.

3.2.1 Equation of head losses in pipes and in junctions

To Study the effect of the head losses in the system the equation below can be used. This equation would be written for each pipe of the network that as a part of system of equations would be solved.

$$\mathrm{H_{US,i}} - \mathrm{H_{DS,i}} = \frac{\mathrm{Q_i|Q_i|}}{\mathrm{A_i}^2 \times 2 \times \mathrm{g}} \left(\sum_{\mathrm{K}=1}^{\mathrm{M_i}} \mathrm{k_k} + \lambda_\mathrm{i} \frac{\mathrm{L_i}}{\mathrm{D_i}} \right)$$

- $\mathrm{H}_{\mathrm{US},i}$: Hydraulic head at the upstream side of pipe i.
- HDS_i: Hydraulic head at the downstream side of pipe i.
- Q_i: Flow rate through pipe i.
- A_i: Cross-sectional area of pipe i.
- g: Acceleration due to gravity.

- K: Minor Loss coefficient.
- λ_i: Friction factor based on Reynolds number and roughness of the pipe
- L_i: Length of pipe i.
- D_i: Diameter of pipe i.

To solve this equation two loss coefficient as below should be defined.

- Minor head losses (K)
- Distributed head losses (λ)

Minor head losses

In water distribution networks (WDNs), minor head losses refer to the pressure drops that occur due to various factors such as bends, fittings, valves, and transitions in the pipe system. These losses, although individually small compared to major losses like frictional losses along the length of pipes, can collectively have a significant impact on the overall performance of the network. Understanding and accounting for minor head losses are crucial for accurate hydraulic modeling and efficient design of water distribution systems.
There are several types of minor head losses encountered in WDNs:

- Friction Losses: These occur due to the resistance encountered by water flow as it passes through fittings, bends, valves, and other components with non-uniform geometries. The friction between the flowing water and the surface of these components causes energy dissipation in the form of pressure drops.
- Expansion and Contraction Losses: When the flow area suddenly expands or contracts within the pipeline, such as at pipe junctions or transitions between pipe sizes, energy is lost due to changes in velocity and flow patterns. This results in additional pressure losses beyond those caused by friction.
- Entrance and Exit Losses: When water enters or exits a pipe, such as through a valve or a sudden change in pipe diameter, there is a loss of kinetic energy due to the disturbance in flow patterns at these locations. These losses are

often characterized by specific coefficients dependent on the type of fitting or component.

- Bend and Elbow Losses: Changes in flow direction, such as bends and elbows, introduce additional resistance to flow, leading to minor head losses. The degree of curvature and the smoothness of the bend surface play crucial roles in determining the magnitude of these losses.

- Valve and Fitting Losses: Various types of valves, including gate valves, globe valves, and check valves, as well as other fittings like tees and reducers, contribute to minor head losses in WDNs. The design and configuration of these components influence the extent of energy dissipation and pressure drops.

Efficient management of minor head losses in water distribution networks involves careful selection of pipe materials, fittings, and components, as well as optimizing the network layout to minimize unnecessary bends and transitions. Hydraulic modeling software plays a vital role in accurately predicting and mitigating these losses, ultimately ensuring the reliable and cost-effective operation of WDNs. The list of minor loss coefficinets of a WDN are shown below:

FITTING	*LOSS COEFFICIENT*
Globe valve, fully open	10.0
Angle valve, fully open	5.0
Swing check valve, fully open	2.5
Gate valve, fully open	0.2
Short-radius elbow	0.9
Medium-radius elbow	0.8
Long-radius elbow	0.6
45 degree elbow	0.4
Closed return bend	2.2
Standard tee - flow through run	0.6
Standard tee - flow through branch	1.8
Square entrance	0.5
Exit	1.0

Figure 3.1: Minor loss coefficients in WDN

Distributed head losses

In water distribution networks (WDNs), distributed head losses refer to the gradual decrease in hydraulic pressure along the length of pipes due to frictional resistance between the flowing water and the pipe walls. These losses are caused by factors such as the roughness of the pipe material, the velocity of flow, and the diameter and length of the pipe. Distributed head losses play a significant role in determining the performance and efficiency of WDNs, as they directly impact the pressure available at consumer points, the flow distribution within the network, and the overall energy consumption of the system. Understanding and accurately estimating distributed head losses are crucial for hydraulic modeling and network analysis, as they influence decisions related to pipe sizing, pump selection, and system operation. Strategies for mitigating distributed head losses include optimizing pipe materials and diameters, minimizing pipe lengths, and implementing efficient network layouts. By effectively managing distributed head losses, water utilities can improve the reliability, efficiency, and sustainability of their distribution networks, ultimately ensuring the reliable delivery of high-quality water to consumers.

Colebrook-White equation

The Colebrook-White equation serves as a fundamental tool in hydraulic engineering for estimating frictional head losses in pipe flow. Derived empirically, it accounts for the complex interplay between pipe roughness, flow velocity, and Reynolds number. By providing a means to calculate the Darcy-Weisbach friction factor, the Colebrook-White equation offers a precise method for predicting head losses in water distribution networks. This equation's versatility allows engineers to model a wide range of pipe materials and flow conditions accurately. Despite its computational complexity, numerous numerical methods and iterative techniques have been developed to solve the Colebrook-White equation efficiently. Its widespread use underscores its importance in hydraulic modeling and underscores its critical role in optimizing network design, assessing system performance, and ensuring efficient water distribution. The Colebrook-White equation is:

$\frac{1}{\lambda} = -2\log\left(\frac{\varepsilon}{D}\frac{3.7}{D} + \frac{2.51}{\mathrm{Re}\sqrt{\lambda}}\right)$

where:

ϵ and D represent the absolute roughness and diameter of the pipe, respectively. Re denotes the Reynolds number. λ is the friction factor. Knowing all the parameters the friction factor can be derived from this equation.

3.2.2 Mass Continuity formulas at junctions

The next equation would be solved for each junction of WDN.

$\sum_{i \in \mathbf{E}_j} Q_i - \sum_{i^* \in \mathbf{L}_j} Q_{i^*} = 0$

Based on this equation the total amount of flow rate entering a junction Q_i is equal to total amount of the flow rate leaving a junction which can also go out the junction in the form of user demand and leakages.

3.2.3 Boundary conditions of the network (reservoir)

To solve the system of equations the Hydraulic head at the upstream of the node connecting to the reservoir $\mathrm{H}_{\mathrm{US,i}}$ is equal to H_{r} which is the hydraulic head of the reservoir. It should be mentioned that hydraulic head of the reservoir would be considered constant.

$H_{\mathrm{US},i} = H_{\mathrm{res}}$

3.3 Hydraulic modelling in EPANET

In order to model the hydraulics of a WDN with the (generic) characteristics previously highlighted, a standard approach based on the steady state modelling of extended-periods with spatially and temporally varying water demand is adopted. This approach is implemented by the well-known and well-documented software EPANET. The iterative approach for identifying the most optimized sequence utilizes the EPANET-Matlab-Toolkit through the implementation of requisite algorithms within the MATLAB environment as described below. EPANET is a software application designed for extended period simulation of hydraulic and water quality dynamics in pressurized pipe networks. It monitors water flow within pipes, node pressures, and tank water levels. Primarily developed as a research tool, EPANET aids in comprehending the movement and fate of drinking water components in distribution systems. Its versatility extends to various applications such as sampling program design, hydraulic model calibration, chlorine residual analysis, and consumer exposure assessment. By facilitating the evaluation of alternative management strategies, EPANET contributes to enhancing water quality systemwide. Operating on Windows, EPANET offers a comprehensive platform for editing network data, conducting hydraulic and water quality simulations, and visualizing results through network maps, data tables, time series graphs, and contour plots.

3.3.1 Hydraulic Modeling Capabilities of EPANET

EPANET presents a comprehensive array of hydraulic modeling capabilities crucial for effective water quality analysis. Its sophisticated hydraulic analysis engine incorporates the following functionalities [18]:

- **Scalability:** EPANET imposes no restrictions on the size of the network under analysis, ensuring adaptability to varying system complexities.
- **Friction Headloss Computation:** Employing industry-standard formulas like Hazen-Williams, Darcy-Weisbach, or Chezy-Manning, EPANET accurately computes friction headloss, enabling precise assessment of flow dynamics.
- **Consideration of Minor Head Losses:** The software meticulously factors in minor head losses arising from bends, fittings, and other components, offering a nuanced portrayal of system behavior.
- **Modeling of Pumps:** EPANET adeptly simulates both constant and variable speed pumps, facilitating precise evaluation of pumping operations.
- **Pumping Energy and Cost:** Through comprehensive calculations, EPANET determines pumping energy consumption and associated costs, aiding in cost-benefit analyses and optimization of pumping strategies.
- **Valve Modeling:** EPANET accommodates various valve types, including shutoff, check, pressure-regulating, and flow control valves, enabling detailed modeling within the network.
- **Storage Tank Flexibility:** EPANET provides flexibility in modeling storage tanks of any shape, allowing for variations in diameter with height to accurately reflect real-world tank configurations.
- **Demand Variation Modeling:** Supporting multiple demand categories at nodes, each with its unique time variation pattern, EPANET enables comprehensive demand analysis.

- **Pressure-Dependent Flow Modeling:** EPANET proficiently models pressure-dependent flow from emitters such as sprinkler heads, capturing the nuances of water distribution in diverse scenarios.

- **System Operation Controls:** Offering flexibility in system operation, EPANET accommodates both simple tank level or timer controls and complex rule-based controls to govern system behavior.

3.3.2 Project modelling in EPANET

To begin a project in EPANET, the initial step involves creating a new project. Subsequently, utilizing the drawing toolbar, proceed to sketch the various components of the network, encompassing Reservoirs, Junctions, Tanks, Pipes, and Pumps.

The pump curves can be inputted into the model, as illustrated below as a sample:

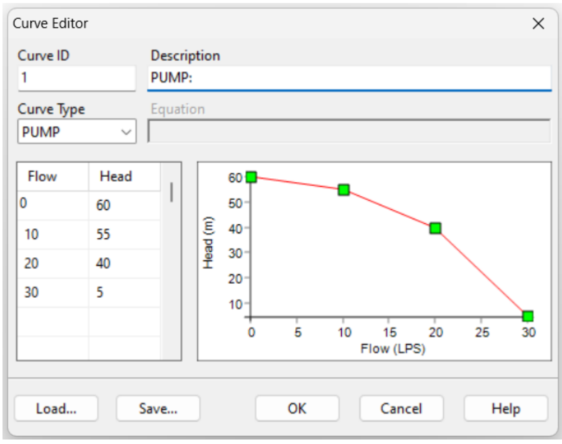


Figure 3.2: Sample of pump curve

The time pattern of demand within the network, derived from data provided by responsible authorities, can be imported into the model as demonstrated below:

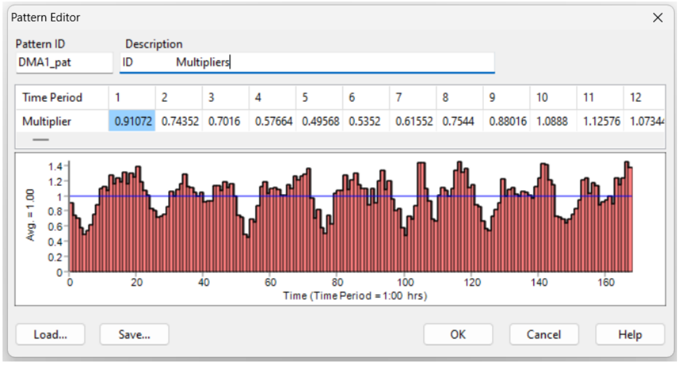


Figure 3.3: Sample of time pattern of demand

The network's control rules, determining the activation and deactivation of pumps based on tank water levels, should be inputted into the model according to the sample illustration provided below:

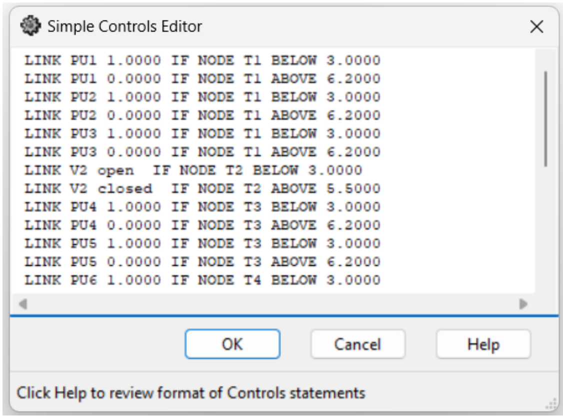


Figure 3.4: Sample of controls of the network

At the conclusion of the process, users can utilize the "time option" to specify the duration of the simulation, subsequently running the model to observe the results. These results can be visualized on the maps, as demonstrated by an example result of pressure in the network shown below. Additionally, users can further explore the data by positioning the mouse cursor over the desired junction or pipe, and extract additional insights through graphs and tables, exemplified as follows:

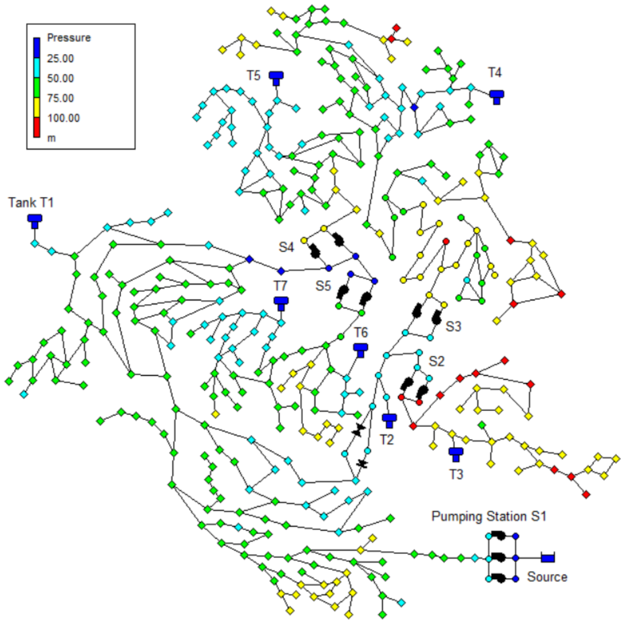
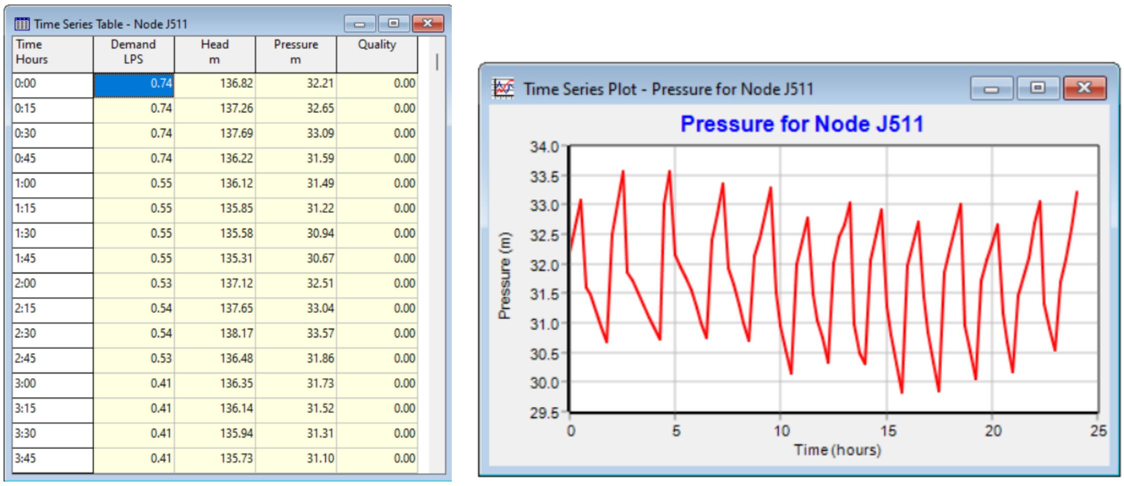


Figure 3.5: Sample of results of pressure shown on the network map



Time Series Table - Node J511

Time Hours	Demand LPS	Head m	Pressure m	Quality
0:00	0.74	136.82	32.21	0.00
0:15	0.74	137.26	32.65	0.00
0:30	0.74	137.69	33.09	0.00
0:45	0.74	136.22	31.59	0.00
1:00	0.55	136.12	31.49	0.00
1:15	0.55	135.85	31.22	0.00
1:30	0.55	135.58	30.94	0.00
1:45	0.55	135.31	30.67	0.00
2:00	0.53	137.12	32.51	0.00
2:15	0.54	137.65	33.04	0.00
2:30	0.54	138.17	33.57	0.00
2:45	0.53	136.48	31.86	0.00
3:00	0.41	136.35	31.73	0.00
3:15	0.41	136.14	31.52	0.00
3:30	0.41	135.94	31.31	0.00
3:45	0.41	135.73	31.10	0.00

(a) Table (b) Graph

Figure 3.6: Sample table and graph outputs

3.4 EPANET-Matlab-Toolkit

EPANET provides a powerful platform for analyzing water distribution network models over extended periods, offering results in various formats. However, the optimization process entails evaluating the network across numerous scenarios, involving different sequences of pipe disconnections. Performing these tasks directly within EPANET would require manually disconnecting pipes in the software, running simulations, obtaining results, and repeating this process for each sequence. Given the multitude of simulations required for each scenario and the number of pipes involved, manual execution becomes prohibitively time-consuming and resource-intensive. As such, directly employing EPANET for this purpose is impractical.

In response to this challenge, automation emerges as a critical solution. By leveraging scripting capabilities and using EPANET-Matlab-Toolkit, the simulation process can be streamlined. Through the development of scripts, simulations can be programmatically orchestrated, enabling systematic alteration of pipe disconnection sequences, collation of results, and analysis. This automation not only alleviates the burden of manual intervention but also facilitates the exploration of a broader array of scenarios within a more efficient timeframe.

The proposed methodology encompasses several key steps. Firstly, an understanding of the EPANET-Matlab-Toolkit for programmatic interaction is essential. Subsequently, the development of scripts tailored to automate simulation runs, encompassing the generation of diverse pipe disconnection sequences and the execution of simulations, becomes paramount. Following simulation runs, the collection and analysis of results permit the identification of optimal solutions in alignment with predefined optimization criteria. This iterative process facilitates the refinement of network designs, fostering continual improvement and enhancement. [6]

3.4.1 Commands for using in MATLAB

To begin using the toolkit, firstly the toolkit should be downloaded from GitHub and then should be inserted in the folder of the code.
https://github.com/OpenWaterAnalytics/EPANET-Matlab-Toolkit/releases
After setting up the toolkit, it is needed to create a script to connect MATLAB with EPANET. Below is a sample code demonstrating how to open the toolkit and execute a set of commands used in this study:

```
start_toolkit; %starting the toolkit
G = epanet('Network.inp'); % Load EPANET input file 'Network.inp' to Matlab
G.getNodeCount; % Get number of nodes
G.getLinkCount; % Get number of links
G.NodeTankCount; % Get number of tanks
G.getNodeIndex; % Get the index of nodes in the network
G.getLinkPumpIndex; % Get the index of pumps
G.getLinkNodesIndex; % Retrieves the indexes of the from/to nodes of all links
G.getNodeTankIndex; %Retrieves the indices of tanks
G.getNodeReservoirIndex; %Retrieves the indices of reservoirs
G.openHydraulicAnalysis; %Opens the hydraulics analysis system
G.initializeHydraulicAnalysis; %Initializes storage tank levels,
link status and settings, and the simulation clock time
G.getTimeSimulationDuration;%Retrieves the value of simulation duration
G.runHydraulicAnalysis; %Runs a single period hydraulic analysis,
G.getNodeEmitterCoeff; %Retrieves the value of all node emmitter coefficients
```

3.4.2 Hydraulic Modeling with EPANet

It is of interest to reformulate the continuity equations that hold at junctions as:

$$\sum_{i \in E_j} Q_i - \sum_{i \in L_j} Q_i - \hat{Q}_j = 0, \tag{3.1}$$

where E_j is the list of links that enter the junction (indicating that the downstream end of the link merges in the junction), and L_j is the list of links that leave the junction (indicating that the upstream end of the link merges in the junction).

Here, $\hat{Q}_j$ represents the total outflow from the junction, composed of a term caused by users ($Q_{D,j}$) and a term caused by leakages occurring along pipes. The key term here is $Q_{L,i,j}$, representing the leakage that occurs over the i-th pipe and is aggregated at the j-th junction. To evaluate this term, it is assumed that the leakage depends on the pressure occurring at the j-th junction. Under this assumption, the leakage can be evaluated as:

$$Q_{L,i,j} = \frac{1}{2}\xi_{L,i} L_i \sqrt{P_j}, \tag{3.2}$$

where $\xi_{L,i}$ represents the coefficient of the orifice flow, which depends on the length of the pipes connected at the junctions and on the characteristics of the pipe.

This approach models leakages along a pipe as an orifice flow, with the flow coefficient of the orifice ($\xi_{L,i} = \frac{1}{2} L_i \xi_{L,i}$) depending on half of the length of the pipes connected at the junctions and on the characteristics of the pipe.

3.4.3 Modeling the Variation of Hydraulic Characteristics and WDN Topology

A key step in this work is modeling the variation of hydraulic characteristics and Water Distribution Network (WDN) topology brought about by single operations of renovation. Among the different possible operations, the focus is restricted to the replacement of links, although other operations can be accounted for with the same approach.

The replacement of a link between two junctions consists of different phases. To better illustrate these phases, Figures 1a-1c focus on the replacement of the pipe

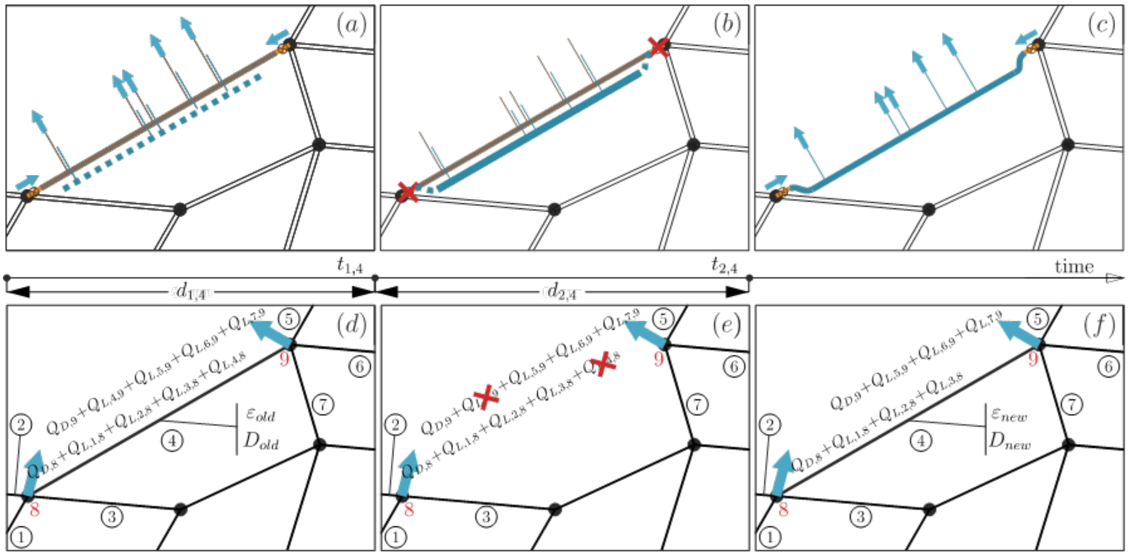


Figure 3.7: Sample of controls of the network

characterized by the link with index $i = 4$.

During the first phase (Panel a, duration $d_{1,4}$), preliminary works for the installation of the new pipe (blue) are done. These preliminary works entail the excavation of the trench for the new conduit, the laying of pipes, and the installation of connections with buildings. The first phase ends at the calendar time $t_{1,4}$.

During the second phase (Panel b, duration $d_{2,4}$), the old pipe is disconnected from the network (valves connecting the pipe with the junctions are closed), and connections with the new pipe are installed. The second phase ends at the calendar time $t_{2,4}$.

In the third phase (Panel c), the valves connecting the new pipe with the junctions are opened, and the new pipe becomes operational.

The three phases previously discussed are now interpreted from a hydraulic modeling perspective. Figures 1d-1f will help for this purpose. The pipes (or other links) to be replaced are identified with the index k (introduced to differentiate them from the generic i-th link). R is the list of links to be replaced. In Figures 1d-1f, $k = 4$.

It should also be noted that the upstream (US) end of the pipe merges in junction 8, whereas the downstream (DS) end merges in junction 9 (see the red numbers in Figures 1d-1f).

Phase one (generic duration $d_{1,k}$) spans until the condition $t \leq t_{1,k}$ holds. During this phase, the generic k-th pipe to be replaced is characterized by the old values of roughness $\varepsilon_{\text{old},k}$ and old diameter $D_{\text{old},k}$. The demand at nodes $\hat{Q}_8$ and $\hat{Q}_9$ is evaluated with Equation (2). All pipes merging at the junctions contribute to induce leakages.

In phase two (generic duration $d_{2,k}$), the generic k-th link to be replaced is disconnected from the network. The pipe is removed from the network topology, and the status "closed" is set for the link. Leakages induced by the considered pipe to be replaced are set to zero during this phase.

Phase three begins when $t > t_{2,k}$. During this phase, the generic k-th pipe to be replaced is connected back to the network (the status "open" is set for the link). Now characterized by the new value of roughness $\varepsilon_{\text{new},k}$ and new diameter $D_{\text{new},k}$, leakages induced by the considered pipe to be replaced are set to zero.

All operations were scheduled in calendar time, as they interfere with a dynamically evolving system.

The duration in hours $d_{1,k}$ and $d_{2,k}$ for all $k \in R$ were determined. The possible working days and hours during which preliminary works (phase one) or disconnections (phase 2) could be performed were determined (e.g., Monday-Friday, 8 AM-4 PM). An algorithm implemented in MATLAB was adopted for the allocation of working activities.

3.4.4 Pipe replacement process

There are several tasks involved in the process of pipe replacement, focusing on the replacement of one pipe at a time. The steps for each replacement are outlined as follows:

3.4.5 Step 0: Planning the works

Planning the process of pipe replacement typically begins with the creation of a Work Breakdown Structure (WBS). The WBS breaks down the project into smaller, more manageable components, providing a hierarchical framework that helps organize tasks and allocate resources effectively. Each component represents a specific

aspect of the project, such as assessment, material procurement, installation, testing, and cleanup. By structuring the project in this manner, it becomes easier to define the scope of work, identify dependencies between tasks, estimate timelines and costs accurately, and assign responsibilities to team members or contractors. The WBS serves as a foundation for developing detailed project schedules, resource plans, and budgets, facilitating efficient execution and monitoring of the pipe replacement process from start to finish.
To visualize the project timeline in MATLAB, a code has been formulated to delineate working days highlighted in gray and weekends depicted in white. Along the x-axis, the temporal progression from the project's inception to its culmination is denoted in hours.

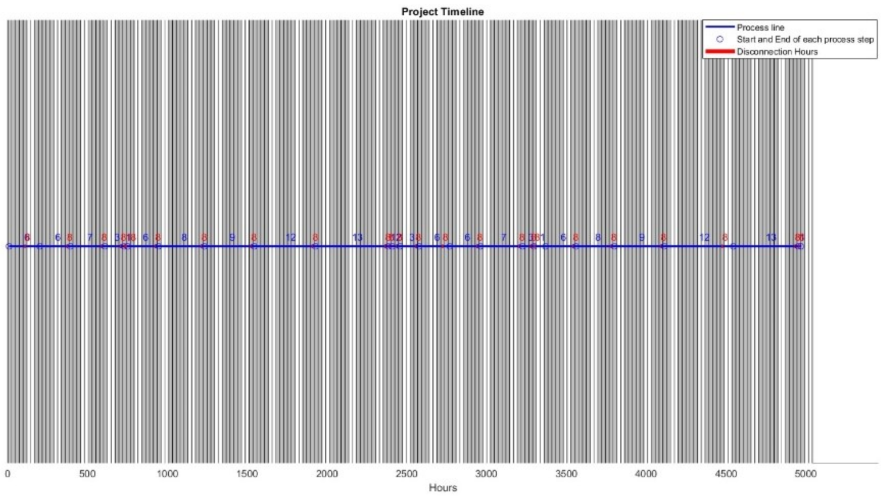


Figure 3.8: Timeline of the project

The timeline illustrates the project duration T_W in blue, alongside the total duration of each pipe replacement d_k also depicted in blue numbers. Additionally, the hours during which each pipe is disconnected from the network for replacement, denoted as $d_{2,k}$, are highlighted in red numbers. This comprehensive visual aid facilitates the contractor's planning and organization of the project, enabling efficient scheduling and resource allocation.

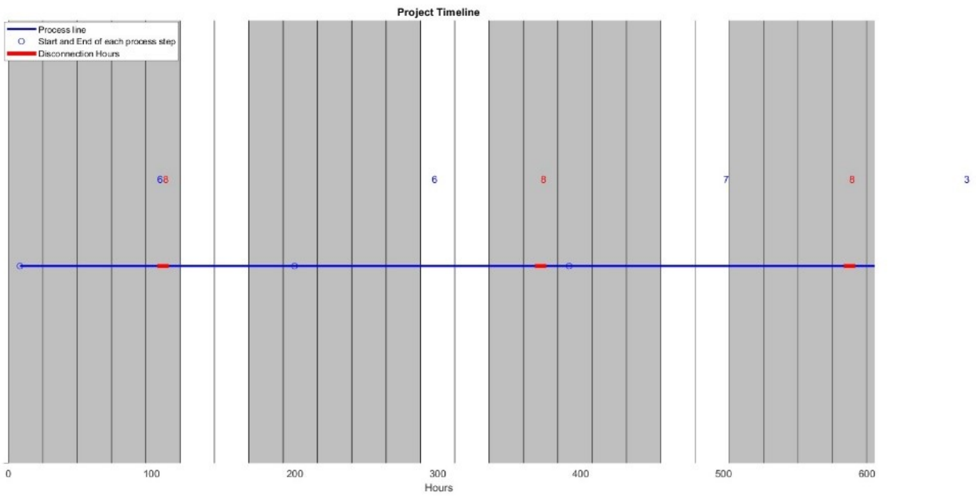


Figure 3.9: Timeline of the project (magnified view)

Step 1: Preliminary Works for Installation of the new pipe

The preliminary works for the installation of a new pipe are critical in ensuring the success of the replacement process. This phase involves several key activities aimed at preparing the site and resources necessary for the installation.

Firstly, a thorough site assessment is conducted to identify the location and condition of existing utilities, such as other underground pipes, cables, or infrastructure. This assessment helps prevent accidental damage to these utilities during excavation and installation activities.
One methos is using Ground-Penetrating Radar (GPR) systems.Ground-penetrating radar (GPR) is a geophysical method that uses radar pulses to image the subsurface. It is a non-destructive technique that provides high-resolution images of the shallow subsurface, typically up to a depth of about 100 feet (30 meters), although penetration depths can vary depending on factors such as soil conditions and the frequency of the radar signal used. The basic principle of GPR involves transmitting short pulses of high-frequency electromagnetic waves (typically in the microwave range) into the ground using an antenna. These waves penetrate the subsurface and are reflected back to the surface when they encounter changes in the electrical properties of the materials they encounter, such as changes in soil composition, the presence of buried objects, or interfaces between different geological layers. By

analyzing the time it takes for the reflected signals to return to the surface and their amplitude, GPR systems can create detailed images of subsurface features. The data collected can be processed to generate cross-sectional views of the subsurface, similar to a slice through the ground, revealing buried objects, geological structures, archaeological artifacts, utilities, and other subsurface features. [23]
The study conducted by Gamal et al. provides a comprehensive investigation into the use of ground-penetrating radar (GPR) for water leak detection and pipe material characterization, focusing on urban environmental studies. Utilizing a finite-difference time-domain (FDTD) method for numerical modeling and a GPR field survey with a 600 MHz antenna in Egypt's El Hammam area, the authors demonstrate the efficacy of GPR in identifying water pipe leaks and distinguishing between various pipe materials under different field conditions. Employing envelope and migration techniques, they accurately differentiate between pipe types, particularly in leak areas. This research underscores the reliability of GPR as a non-destructive tool for detecting water pipe leaks and characterizing pipe materials, crucial for effective management and maintenance of water distribution systems (Gamal et al., [2023]). [7]
A study by Solla et al. [2017] [20] provides guidelines for efficient field data acquisition using Ground-Penetrating Radar (GPR) for detecting underground pipes, crucial for smooth construction processes and minimizing utility service disruptions. Four antenna frequencies (2.3 GHz, 1 GHz, 800 MHz, and 500 MHz) were tested, with 2.3 GHz offering better results for shallower pipes and 1 GHz/800 MHz for deeper ones. Adjusting total time windows (e.g., 10 ns for 2.3 GHz, 30 ns for 1 GHz/800 MHz) and maintaining a 2 cm spatial sampling interval are recommended. Antenna orientation influences resolution, with perpendicular dipoles enhancing vertical resolution and parallel dipoles improving horizontal resolution. Simulation of various pipe materials, depths, and configurations aids in understanding radar-wave responses. Results indicate that the 2.3 GHz frequency provides better outlying of pipe signatures for shallower pipes, while 1 GHz and 800 MHz frequencies allow detection at greater depths. Proper data analysis and consideration of environmental factors are crucial for accurate interpretation of GPR results, ensuring effective detection and location of buried pipes in construction projects.

Next, any necessary permits or approvals required for the replacement project are obtained from relevant authorities. These permits may include environmental permits, construction permits, or permissions from local municipalities.

Once the site assessment and permits are obtained, the area around the replacement site is prepared. This may involve clearing vegetation, removing debris, and ensuring adequate access for construction equipment and vehicles.

Materials and equipment required for the installation are procured and prepared. This includes the new pipe sections, fittings, valves, and any specialized tools needed for the installation process.

Finally, safety measures are put in place to protect workers and the surrounding environment during the replacement process. This includes implementing proper signage, erecting barriers around the work area, and providing personal protective equipment (PPE) for workers.

Overall, the preliminary works phase sets the foundation for a successful pipe replacement project by ensuring that all necessary preparations are made before commencing with the physical installation activities.

Step 2: Excavation of Trench

The excavation of a trench is a crucial step in the pipe replacement process, as it provides the necessary space for removing the old pipe and installing the new one. This phase involves careful planning and execution to ensure safety and efficiency. Before excavation begins, the site is marked to indicate the route of the trench and any potential hazards or obstacles that need to be avoided. This may include underground utilities, tree roots, or other buried structures.

Excavation equipment, such as backhoes or trenching machines, is used to dig the trench to the required depth and width. Excavated soil is typically stockpiled nearby for later use or disposal, depending on project requirements and local regulations. Throughout the excavation process, workers monitor the trench for stability and safety hazards, such as cave-ins or soil collapse. Protective measures, such as shoring, sloping, or benching, may be employed to prevent accidents and ensure worker safety. Once the trench is dug to the required depth, it is inspected to ensure it meets project specifications. Any necessary adjustments or corrections are made before proceeding to the next phase of the replacement process. Overall, the excavation of the trench is a critical step that lays the groundwork for the successful installation of the new pipe, and careful planning and execution are essential to ensure safety and efficiency.

Step 3: Laying of the New Pipe

The laying of the new pipe is a pivotal step in the replacement process, as it involves positioning and securing the new pipe within the excavated trench. This phase requires precision and attention to detail to ensure proper alignment and functionality of the new pipe. Before laying the new pipe, workers carefully inspect the trench to ensure it meets the required specifications in terms of depth, width, and alignment. Any necessary adjustments or corrections are made to ensure a proper foundation for the new pipe.

Next, sections of the new pipe are transported to the site and carefully lowered into the trench using equipment such as cranes, hoists, or excavators. Workers ensure that the pipe sections are properly aligned and supported to prevent damage during installation.

As the new pipe is laid in the trench, workers make connections between pipe sections using appropriate fittings, such as couplings, flanges, or welds. These connections are crucial for maintaining the integrity of the pipeline and preventing leaks or failures.

Throughout the laying process, workers pay close attention to the slope and alignment of the pipe to ensure proper drainage and flow characteristics. Any deviations from the desired specifications are corrected promptly to avoid future issues.

Once all pipe sections are in place and properly connected, the trench is backfilled with excavated soil, compacted, and graded to restore the site to its original condition. Any excess soil is removed from the site and disposed of according to local regulations.

Overall, the laying of the new pipe is a critical phase in the replacement process that requires careful planning, execution, and attention to detail to ensure the successful installation and functionality of the new pipeline.

Step 4: Preparation of Connection with Users Along the Pipe

The preparation of connections with users along the pipe is an essential step in the pipe replacement process, ensuring that individuals or entities dependent on the utilities provided by the pipeline have uninterrupted access during and after the replacement.
This phase involves several key activities to establish connections and maintain service continuity:

Steps for Pipeline Replacement

- **Identification of Users:** The first step is to identify all users or properties that receive services from the pipeline being replaced. This may include residential, commercial, or industrial properties, as well as public facilities such as schools or hospitals.

- **Communication and Coordination:** Once users are identified, communication is established to inform them of the upcoming replacement project. This includes notifying users of any temporary disruptions to service and providing information on alternative arrangements, if necessary.

- **Inspection and Assessment:** Prior to replacing the pipe, each user connection point is inspected to assess its condition and suitability for connection to the new pipeline. Any necessary repairs or upgrades to user connections are made to ensure compatibility with the new system.

- **Installation of Connection Points:** New connection points are installed along the length of the new pipeline to facilitate the distribution of utilities to users. This may involve installing valves, meters, or other fittings at strategic locations to regulate flow and monitor usage.

- **Testing and Verification:** Once connections are installed, each connection point is tested to ensure proper functionality and integrity. This may include pressure testing, leak detection, and flow testing to verify that the connections are secure and operational.

- **Documentation and Records:** Detailed records are maintained throughout the process to document the location and condition of each user connection, as well as any modifications or upgrades made during the replacement project. This documentation helps ensure accountability and facilitates future maintenance and management of the pipeline system.

Overall, the preparation of connections with users along the pipeline is a critical phase in the replacement process, requiring careful planning, communication, and coordination to minimize disruptions and ensure the continued delivery of essential utilities to end users.
This sequence outlines the systematic process involved in replacing a pipe, with a focus on ensuring efficiency and effectiveness in each step.

3.4.6 Implementation of Modeling

Figure 2 depicts the algorithm adopted to model the sequence of replacement of all links listed in R. For simplicity, only pipes are taken into account.

The core of the algorithm is to simulate a Water Distribution Network (WDN) with evolving topology and hydraulic characteristics. To achieve this, a cycle of simulations of the WDN is conducted over time t (yellow rectangles in Figure 2). The flow of time is occasionally interrupted to perform required modifications of topology or hydraulic characteristics. These interruptions are governed by two parameters: $t_{\max}$ and "type". The parameter $t_{\max}$ sets the time when simulations on the WDN are to be stopped, and its characteristics are to be updated (orange rhombus in Figure 2). The parameter "type" sets the type of modification to be performed: closure of the pipe or opening of the pipe with updated diameter, roughness, leakages (green rhombus in Figure 2).

To better understand the algorithm, a typical cycle (see arrow in Figure 2) is followed and discussed.

The first step is to load all data of the WDN prior to renovation works. This includes producing an input file for a WDN modeling software. In this work, EPANet was used, so an ".inp" file was written. Additionally, the calendar time of each operation for each pipe to be replaced is loaded. The renovation works begin at $t = t_0$ and end at $t = t_0 + T_W$.

The second step is to initialize the time at the value $t = t_0$, set $t_{\max} = t_{1,k}$, and $type$ = close. The first setting defines the next calendar time for a modification of the network, and the second setting defines the type of the next modification.

The third step is to simulate the network behavior until $t \leq t_{\max}$ (yellow rectangles in Figure 2). For each time step Δt, the values of pressure and demand at junctions are saved in time series $P_j(t)$ and $Q_j(t)$. Other data such as tank levels $H_{T,\tau}(t)$, and the status of dynamical elements (e.g., valves, pumps) are also saved.

When t exceeds $t_{\max}$, the cyclic modeling of the WDN is interrupted (orange rhombus in Figure 2). If $t < t_0 + T_W$, an operation on pipes is performed. The saved levels of tanks $H_{T,\tau}(t)$ and the status of all dynamical elements are loaded.

Two paths can be followed, depending on the operations to be performed (green rhombus in Figure 2). One possible operation is the closure of the pipe (pink rectangles). This entails setting leakages induced by the k-th pipe to zero and disconnecting the pipe. Additionally, $t_{\max}$ is set to $t_{2,k}$ and $type$ = replace.

The other possible operation is to put the new pipe into service (light blue rectangles). This involves modifying the roughness and diameter of the k-th pipe to the new values, connecting the pipe, and keeping leakages induced by the k-th pipe to zero. Additionally, $t_{\max}$ is set to $t_{1,k+1}$ and $type$ = close.

A new input file for a WDN modeling software is written to implement these modifications. Afterward, new simulations with the updated network can be performed (red arrow in Figure 2). The MATLAB toolkit for EPANet was chosen for implementing this sequence of operations.

In summary, the typical results of one simulation of WDN renovations include the time series of pressure in each junction $P_j(t)$ and the time series of demand in each junction $Q_j(t)$. These time series can be analyzed to evaluate additional time-series useful for determining the effect of the replacement works on users, such as demand deficit, leakages in all junctions, and energy consumed by all pumps.

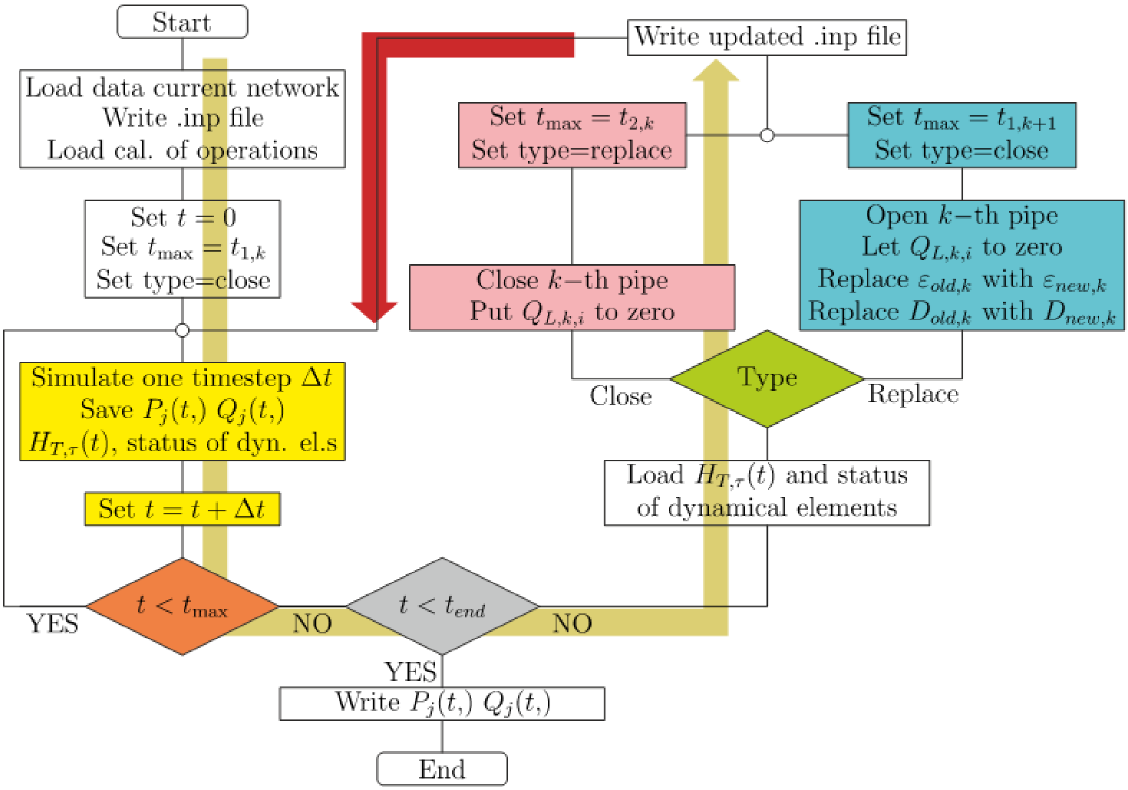


Figure 3.10: Sample of controls of the network

3.4.7 Estimation of Costs

During the process of Water Distribution Network (WDN) renovation, pipes (or other link elements) will be progressively replaced. This sequence of replacements will induce changes in the pressure within the network, leading to two relevant effects.

The first effect arises during the disconnection period (from $t_{1,k}$ to $t_{2,k}$) at the nodes where the k-th pipe is connected to the network, resulting in a reduction of pressure experienced, potentially increasing the demand deficit $\Delta Q_j(t)$.

The second effect occurs after the disconnection period, reducing leakages and potentially increasing pressure at the junctions of the k-th pipe. This can reduce the demand deficit $\Delta Q_j(t)$ but increase leakages in pipes that are not yet replaced.

User Cost Scenarios

One first cost is the so-called "user cost". "User" because we measure the effect of pipe replacement on user's satisfaction. In this perspective, the emphasis is on minimizing demand deficit. Demand deficit in each junction at each time step is $\Delta Q_j(t) = Q_{DU,j} - Q_{D,j}(t)$.
Two scenarios based on user cost can be defined:

- Total demand deficit: sum of the demand deficit in all the junctions of the network over T_W:
$$C_{tdd} = \sum_{j=1}^{N_j} \int_0^{T_W} \Delta Q_j(t)\, dt$$

- Relative demand deficit: In this scenario, same as the previous one, the focal point lies in the minimization of the demand reduction during the pipe replacement process. Different junctions within the network exhibit distinct levels of importance. The importance depends on the base (average) demand. The same demand deficit $\Delta Q_j(t)$ affects to a different extent users with different average base demand. Users characterized by a high average demand are affected to a lower extent, compared to users with a low base demand. The cost is thus estimated as
$$C_{rdd} = \sum_{j=1}^{N_j} \int_0^{T_W} \frac{\Delta Q_j(t)}{\overline{Q}_{DU,j}}\, dt$$

compliance cost

It is called "Compliance" because we measure the effect of pipe replacement on compliance with contracts (supply of the minimum pressure P_{cmp}). In this perspective, the emphasis is on minimizing the pressure deficit. Based on contracts between water utility and users, the minimum pressure P_{cmp} at each junction should be guaranteed. Pressure deficit at each junction is defined as $\Delta P_j(t) = P_j(t) - P_{cmp}$. If $\Delta P_j(t) > 0$, $\Delta P_j(t) = 0$.
Two scenarios based on compliance cost:

- Total pressure deficit:

$$C_{tpd} = -\frac{1}{Tw}\sum_{j=1}^{N_j}\int_0^{T_W} \Delta P_j(t)\, dt$$

- Relative pressure deficit: In this scenario, akin to the previous one, the focus remains on maintaining water pressure above the minimum accepted threshold P_{cmp} as long as possible, and for the greatest number of users. Different users within the network exhibit distinct levels of importance. The importance depends on the base (average) demand. The same pressure deficit $\Delta P_j(t)$ affects a different number of users, according to their average base demand. Users characterized by a high average demand are affected to a higher extent, compared to users with a low base demand. The cost is thus estimated as

$$C_{rpd} = -\frac{1}{Tw}\sum_{j=1}^{N_j}\int_0^{T_W} \Delta P_j(t) \cdot \overline{Q}_{DU,j}\, dt$$

Chapter 4

Algorithm for the optimization

Optimization, the process of finding the best solution from a set of feasible alternatives, plays a fundamental role in addressing complex problems across numerous domains. From engineering and logistics to finance and healthcare, optimization techniques are indispensable tools for improving efficiency, minimizing costs, and maximizing performance.

A study by Liang Yongtu et al. [14] presents an optimization model for multi-product pipelines, focusing on minimizing electricity costs while meeting operational constraints. It accounts for variations in pump station configurations due to batch transportation and considers regional differences in electricity prices. Dynamic programming is used to optimize pump configurations and minimize electricity costs. A case study of the Southwestern Multi-product Pipeline demonstrates the model's effectiveness, achieving significant cost savings by considering regional electricity price differences. The study concludes that incorporating regional electricity price disparities is crucial for optimizing pipeline operations and reducing overall costs. However, it suggests further analysis on the model's stability and sensitivity for future research. Overall, the paper provides valuable insights into optimizing multi-product pipeline operations under varying electricity prices, benefiting pipeline operators and energy management strategies.

In another study, the paper "Optimization of Water Distribution for Open-Channel Irrigation Networks" introduces a comprehensive method for scheduling water demand in open-channel irrigation networks. Through an optimization framework, the authors maximize adequacy between supplied and demanded start time and volumes while minimizing water losses and gate operations. By incorporating constraints related to physical infrastructure, flow routing processes, water resources, and manpower, the method offers flexible decision-making for irrigation start time and volume. Results demonstrate the effectiveness of the approach in optimizing water distribution in a typical open-channel network in southern France.(Hong et al., 2014). [9]

In this discussion, we delve into the significance of optimization in modern problem-solving endeavors.

Enhanced Efficiency and Resource Utilization

Optimization algorithms enable organizations to make the most efficient use of available resources, whether it be time, manpower, or capital. By identifying the optimal allocation of resources, businesses can streamline operations, minimize waste, and maximize productivity. For example, in manufacturing, optimization techniques can optimize production schedules, minimize inventory costs, and reduce lead times, leading to significant cost savings and improved competitiveness.

Decision Support and Strategic Planning

Optimization provides decision-makers with valuable insights and guidance in strategic planning and decision-making processes. By quantitatively analyzing various scenarios and trade-offs, optimization models help identify the best course of action to achieve desired objectives. Whether it's determining the optimal investment portfolio, designing supply chain networks, or scheduling transportation routes, optimization empowers decision-makers to make informed and data-driven decisions that align with organizational goals and priorities.

A study by Oluwadare Joshua Oyebode [2018] [16] presents a method for optimizing the design of water distribution networks in Nigeria, crucial for integrated water supply management in developing nations. Using pipe diameter as a decision variable, informed by field study data, the optimization model aims to determine the most economical pipe sizes under required demand loading and hydraulic conditions. Results indicate that increasing minimum pressure reduces the required pipe diameter, lowering installation costs. Predominantly, pipe sizes of 100 mm and 150 mm are optimal, with larger diameter pipes unnecessary at higher minimum pressure values. The study underscores the importance of well-designed hydraulic structures and regular maintenance for system functionality and durability. Recommendations include awarding construction projects to engineering experts and conducting regular inspections to identify potential issues. Overall, the optimization model offers valuable insights for determining economical pipe sizes in water supply systems, aiding in both planning new systems and evaluating existing networks for upgrades.

Complex Problem Solving and Innovation

Many real-world problems involve numerous interconnected variables and constraints, making them difficult to solve using traditional methods. Optimization techniques offer systematic approaches to tackle these complex problems, providing scalable solutions that leverage computational power and mathematical rigor. From designing efficient telecommunications networks to optimizing energy distribution systems, optimization fosters innovation by enabling the development of novel solutions to challenging problems.

Sustainability and Environmental Impact

In an era of increasing environmental awareness, optimization plays a crucial role in promoting sustainability and mitigating environmental impact. By optimizing processes and systems to minimize resource consumption, waste generation, and carbon emissions, organizations can operate more sustainably and contribute to environmental conservation efforts. Optimization techniques are employed in various sustainability initiatives, such as renewable energy planning, waste management optimization, and sustainable transportation planning, to promote eco-friendly practices and reduce ecological footprints.

Continuous Improvement and Adaptation

Optimization is not a one-time endeavor but rather a continuous process of refinement and adaptation. By continuously optimizing processes, organizations can adapt to changing market conditions, technological advancements, and evolving customer demands. Through techniques such as continuous improvement methodologies and adaptive optimization strategies, businesses can stay agile, competitive, and responsive in dynamic environments, driving ongoing innovation and growth.

4.1 PBIL Algortihm

In order to optimize the sequence of replacement, the so-called Population Based Incremental Learning (PBIL) algorithm is used. PBIL is a probabilistic optimization algorithm that belongs to the class of estimation of distribution algorithms

(EDAs). Understanding how to implement this algorithm requires defining several variables and parameters.
The article "Optimisation Using Population Based Incremental Learning (PBIL)" by Hughes (1998) [10] provides guidelines for parameter tuning and includes an example implementation in MATLAB. Furthermore, the article discusses techniques for reducing processing overhead, such as utilizing a binary search tree to store chromosome patterns and corresponding objective values. The paper concludes with a demonstration of PBIL's effectiveness through experimental results, showing its capability to converge on optimal solutions efficiently across different problem instances.

4.1.1 PBIL Algorithm Steps

Vector I lists all links in the network, while vector R includes all links to be replaced ($R \in I$), with the number of elements of R denoted as N_R. The number of phases of link replacement is denoted as N_m.
In principle, N_m can be different from N_R, as more links can be replaced during a single phase. Here, we focus on the case where $N_m = N_R$.
With these definitions, it becomes clear that the optimization algorithm aims to determine the best sequence of elements listed in vector R, where "best sequence" means that the cost associated with the sequence of R is minimum.
The steps to apply the PBIL algorithm to the specific case discussed here are described below. The focus is on pipes only, but other links can be considered.
Step 1: Definition of the Probability Matrix
Firstly, the probability matrix P^s with size $N_R \times N_R$ is defined. Each element $P^s(k, m)$ represents the probability that pipe k will be replaced during phase m. The superscript s refers to the current iteration in the optimization algorithm. At the beginning of the optimization ($s = 1$), all elements of P^s are initialized to $1/N_R$ (same probability).
Step 2: Generation of a Random Sequence of Pipe Replacement (Sequence Vector)
For each pipe k^*, the phase m during which the pipe will be replaced is determined by generating sample values (i.e., random extraction) from the probability distributions $P^s(k^*, m)$. An example of a sequence vector is $J = [i_5, i_3, i_2, i_{(1)}, i_4, \ldots, i_{N_R}]$,

where i_m is the index of the pipe to be replaced during phase m.

Step 3: Generation of the Population

In this step, a population of N_{rdm} sequence vectors J_η with $\eta = 1 : N_{rdm}$ is created. The sequence vectors are obtained according to Step 2. The population vector is thus $J = [J_1, J_2, \ldots, J_{N_{rdm}}]$.

Step 4: Repairment of the Sequence Vectors

The elements i_m of the η-th sequence vector are randomly chosen from the vector R. These elements are supposed to be unique in each sequence vector J_η of the population J, as each pipe will be changed once in each sequence of operation. The algorithm checks if there are repetitive elements and replaces them with new randomly chosen elements. The procedure is repeated until each sequence vector J_η of the population J includes all the elements of the matrix R.

Step 5: Cost Evaluation for Each Sequence Vector

The cost of the network is calculated for each sequence vector that makes up the population. The sequence vector that provides the lowest cost among the entire population is denoted as J^*.

Step 6: Update of the Probability Matrix

Each row (index k) of the probability matrix in the algorithm at the iteration $s+1$ will be updated as follows. Firstly, the condition $J^*(k) = i_m$ is checked for each element of $J^*(k)$, where $k = 1 : N_R$. This condition identifies when -in the most convenient sequence found so far- the k-th pipe is replaced during the m-th phase. When the condition holds true, the probability of such an event is increased. This is done by modifying the probability matrix as $P^{(s+1)}(k,m) = (1 - LR) \times P^s(k,m) + LR$, where LR is the learning rate. When the condition doesn't hold true, the probability of such an event occurring is reduced. Again, this is done by modifying the probability matrix as $P^{(s+1)}(k,m) = (1 - LR) \times P^s(k,m)$.

Step 7: Probability Matrix Mutation

During optimization, it is possible for algorithms to get stuck in local optimal solutions. Mutations are thus used to escape from these local minimums. In each row k of the probability matrix $P^{(s+1)}$, one element is randomly selected. The selection is done with mutation probability f.

The so-called "direction of mutation" is then randomly determined as $d_f = (-1 \text{ or } 1)$. Mutations are then applied on row k as follows.

For the location (k,m),

$P^{(s+1)}(k,m) = [P^{(s+1)}(k,m) \times (1 - (d_f \times \Delta f))] + (d_f \times \Delta f)$;
For locations other than (k,m) in row k,
$P^{(s+1)}(k,m) = [P^{(s+1)}(k,m) \times (1 - (d_f \times \Delta f))]$,
where Δf is the value of the mutation shift.
If $P^{(s+1)}(k,m) > 1$, the condition $P^{(s+1)}(k,m) = 1$ is set, whereas if $P^{(s+1)}(k,m) < 0$, the condition $P^{(s+1)}(k,m) = 0$ is set.

Step 8: Check the Algorithm Stop Criteria

If the number of prescribed iterations of the algorithms s has reached the pre-set number of iterations NI to be performed, the algorithm is stopped; otherwise, another iteration begins from Step 2.

4.1.2 Review of "Implementation Sequence Optimization for Dedicated Bus Lane Projects"

The paper by Bayrak, Guler [2], and Schonfeld presents a novel methodology for optimizing the sequence and location of dedicated bus lane implementations, employing a Population-Based Incremental Learning (PBIL) algorithm. The study addresses the critical need in transportation planning to minimize disruptions caused by construction while maximizing project benefits and cost-effectiveness. The PBIL algorithm is utilized at the upper level of the bi-level optimization framework proposed in the study. At this level, the algorithm optimizes the sequence of bus lane implementations based on the locations identified by the lower-level simulation. The PBIL algorithm is chosen for its ability to account for the interdependencies between the effects of implementing bus lanes at different locations, a crucial aspect in transportation network development problems. Through rigorous testing on an illustrative network, the study evaluates various scenarios, considering different demand patterns and bus lane configurations. The PBIL algorithm is applied to optimize the implementation sequence for both optimal and non-optimal bus lane configurations, providing insights into the effectiveness of sequence optimization in different scenarios. Key findings of the study include:

- Identification of optimized bus lane locations aiming to minimize total cost, with peripheral links prioritized for implementation.

- Evaluation of implementation sequence optimization for both optimal and non-optimal bus lane configurations using the PBIL algorithm.

- For optimal configurations, sequence optimization yields insignificant benefits due to avoidance of locations with high car impact.
- However, for non-optimal configurations, prioritizing peripheral links and selecting connected bus lane locations significantly reduces the total project cost.

Overall, the study's comprehensive methodology, rigorous testing, and insightful findings highlight the effectiveness of the PBIL algorithm in optimizing the sequence of dedicated bus lane implementations. The findings contribute to advancing the understanding of transportation planning strategies and offer practical implications for real-world applications.

Chapter 5

Case Studies

5.1 Simplified network

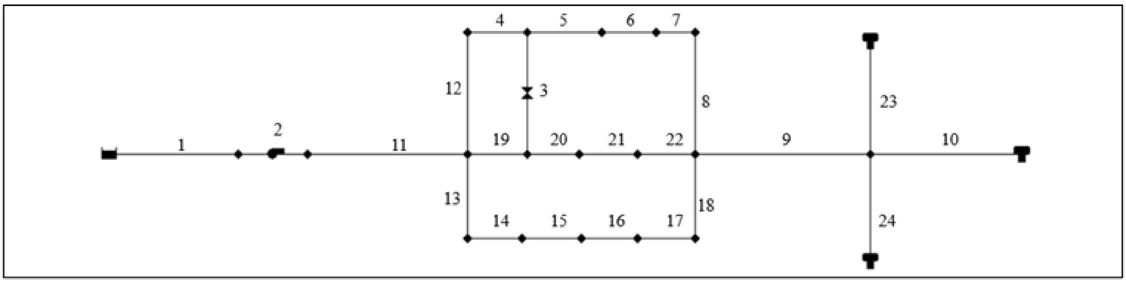


Figure 5.1: Sample of controls of the network

- There are a total number of 22 conduits characterized by lengths in the range of L_i = [100,1000] m, diameters in the range of $D_{old,i}$ = [12,200] mm, and roughness $\varepsilon_{old,i}$ = 1 mm, which will be replaced with new pipes with the length same as before, $D_{new,i} = 150$ mm and $\varepsilon_{new,i} = 0.01$ mm.
- There exist 1 pump possessing a total head of $\Delta H_{\text{P.p}} = 40$ m and flow rate of $Q_{\text{P,p}} = 20$ lps.
- There exists a throttle control valve (TCV) with a diameter of $D_{\text{v}} = 100$ mm and headloss coefficient $C_{\text{V,v}} = 80\%$.
- There are a total of $N_j = 18$ junctions characterized by elevation of $z_{\text{j}} = 0$ m, with user demand $\bar{Q}_{DU,j} = 1$ lps.
- The emitter coefficient within the junctions is set to 0.01 LPS/m$^{0.5}$, resulting in a leakage within the junctions in the range of $Q_{\text{L,j}}$ = [0,8] lps.
- There exists a reservoir with a head of $H_{\text{r}} = 5$ m.
- All 22 pipes, the throttle control valve (TCV), and the pump are scheduled for replacement.
- The total operation time is T_W = 209 days, which includes a total of 24 replacements with d_k = [1,13] days, $d_{1,k}$ = [8,296] hours, and $d_{2,k}$ = 8 hours.
- The minimum acceptable pressure at the junctions is $P_{\text{min,j}} = 14$ m.

5.2 C-Town

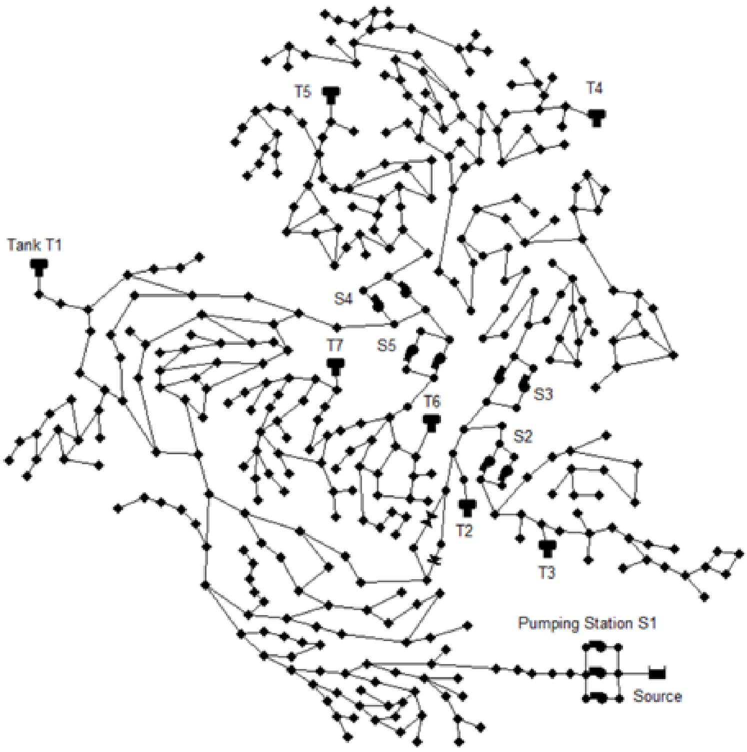


Figure 5.2: Sample of controls of the network

Characteristic of the C-town network are listed below:

- There are a total number of 432 conduits characterized by lengths in the range of $L_i = [4.3, 1280]$ m, diameters in the range of $D_i = [51, 610]$ mm, and roughness ranging $\varepsilon_i = [0.06, 3.62]$ mm. After finishing the operation of pipe replacement, as the pipes are renewed, the roughness of replaced pipes will be $\varepsilon_i = 0.01$ mm.

- There exist 11 pumps possessing a total head of $\Delta H_{\mathrm{P,p}} = [30, 82]$ m and flow rate of $Q_{\mathrm{P,p}} = [26, 100]$ lps.

- There exists a throttle control valve (TCV) with a diameter of $D_{\mathrm{v}} = 254$ mm and headloss coefficient $C_{\mathrm{V,v}} = 80\%$.

- There are a total of $N_j = 388$ junctions characterized by elevation of $z_{\mathrm{j}} = [3.48, 132.5]$ m, with user demand upto $\bar{Q}_{\mathrm{DU,j}} = 1.2$ lps.

- The emitter coefficient within the junctions is set to $[0, 8.64.10^{-4}]$ LPS/m$^{0.5}$, resulting in a leakage within the junctions in the range of $Q_{\mathrm{L,j}} = [0, 3.42]$ lps.
- There exists a reservoir with a head of $H_{\mathrm{r}} = 69$ m.
- Based on the field results, the pipes in district 5 of the network are the most problematic, causing the highest amount of leakages. Therefore, it has been decided to replace all the 53 pipes within this district with new ones.
- The pipes in district 5, are categorized by importance into high (red marked), medium (yellow marked), and low (green marked). High importance pipes necessitate parallel substitutes and immediate attention with lowest disconnection time of one hour, whereas medium importance pipes require replacement within two hours. Conversely, low importance pipes can tolerate a six-hour disconnection due to parallel branches.
- In terms of operation, a 24-hour time pattern is considered, allowing demand to vary in the range of $Q_{\mathrm{DU},j}(t) = [0, 1.66]$ l/s. The total operation time spans $T_W = 216$ days, encompassing 53 replacements with durations $d_{1,k} = [32, 80]$ hours, and $d_{2,k} = [1, 6]$ hours.
- The minimum acceptable pressure at the junctions is $P_{\mathrm{min,j}} = 35$ m.

The list of pipes planned to be replaced and their characteristics are listed below

Table 5.1: Pipe Data (Page 1)

Pipe	Length (m)	Diameter (mm)	Roughness	Importance Level
1	6.75	203.20	0.47	High
2	6.86	152.40	0.18	High
3	26.38	152.40	0.50	High
4	18.65	152.40	0.12	High
5	503.91	102.00	0.29	High
6	157.32	101.60	0.16	Medium
7	80.34	102.00	0.18	Medium
8	11.73	101.60	0.17	Low
9	55.29	101.60	0.22	Medium
10	288.77	152.00	0.31	High
11	190.67	152.00	0.32	High
12	62.20	76.00	0.62	High
13	56.94	152.40	0.12	High
14	89.30	76.00	0.32	Low
15	68.68	76.00	0.24	Low
16	69.88	76.00	0.24	Low
17	119.07	76.00	0.25	Low
18	18.84	76.00	0.16	Low
19	335.29	76.00	0.31	Low
20	6.96	152.40	0.19	Low
21	232.93	102.00	0.26	Low
22	170.64	152.00	0.20	High
23	247.65	152.00	0.15	High
24	295.68	203.00	0.13	High
25	68.63	203.00	0.13	High
26	36.18	203.00	0.54	Low
27	65.80	203.00	0.30	High
28	173.88	152.00	0.13	Medium
29	32.93	152.00	0.15	Medium

Table 5.1: List of pipes in district 5 planned to be replaced

Pipe	Length (m)	Diameter (mm)	Roughness	Importance Level
30	28.98	152.00	0.16	Medium
31	90.81	152.00	0.38	Medium
32	57.47	102.00	0.45	Medium
33	110.79	152.00	0.56	Medium
34	134.92	152.00	0.12	Low
35	195.38	102.00	0.16	Medium
36	17.37	102.00	0.45	Medium
37	37.88	102.00	0.15	Low
38	48.15	102.00	0.46	Medium
39	70.86	102.00	0.17	Low
40	6.42	101.60	0.16	High
41	222.30	102.00	0.21	Low
42	59.38	101.60	0.23	High
43	143.64	102.00	0.21	High
44	12.49	102.00	0.16	Low
45	241.13	101.60	0.17	Low
46	228.78	76.00	0.11	Low
47	86.07	76.00	0.18	Low
48	64.41	52.00	0.38	Low
49	169.49	76.00	0.22	Low
50	76.39	76.00	0.17	Low
51	94.84	203.00	0.25	Low
52	68.63	152.00	0.47	Low
53	40.39	203.00	0.23	High

The schematic of the pipes within district 5 of the network earmarked for replacement is depicted below. Pipes of varying importance are delineated by color coding, with red, yellow, and green denoting high, medium, and low importance, respectively.

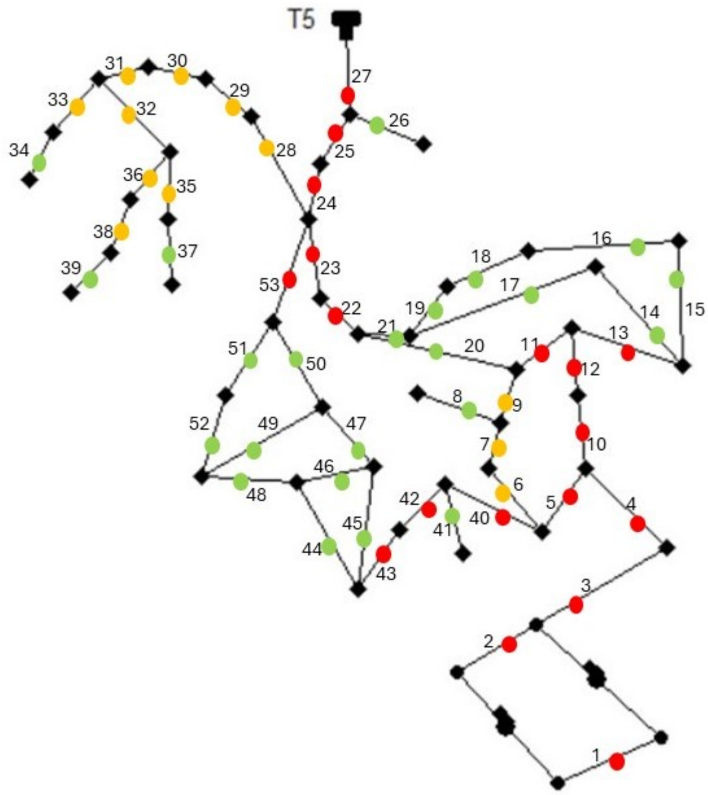


Figure 5.3: Schematic of pipes in district 5 marked by their importance level

Chapter 6

Results

6.1 Simplified network

In this section, the results of simulations conducted on the simplified model will be presented. These findings pertain to two distinct scenarios outlined below:

- User Oriented Scenario
- Compliance Oriented Scenario

It is worth mentioning that since the base demand in the simplified network is $\bar{Q}_{DU,j} = 1$ lps, the relative scenarios are equal to absolute scenarios, so just two scenarios are considered. The random sequence of pipes replacement and the obtained optimised User and Compliance sequences by the algorithm are shown below.

Random and Optimized Sequences of Pipe Replacement																							
Random Scenario								User Oriented Scenario								Compliance Oriented Scenario							
Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe
1	2	7	12	13	24	19	3	1	23	7	15	13	19	19	3	1	11	7	12	13	18	19	22
2	17	8	1	14	23	20	4	2	22	8	16	14	24	20	13	2	13	8	9	14	6	20	17
3	5	9	11	15	18	21	16	3	10	9	5	15	2	21	8	3	8	9	24	15	20	21	3
4	20	10	8	16	9	22	22	4	11	10	12	16	6	22	14	4	14	10	10	16	7	22	23
5	19	11	15	17	7	23	13	5	20	11	18	17	21	23	7	5	19	11	2	17	5	23	21
6	10	12	21	18	6	24	14	6	9	12	17	18	1	24	4	6	15	12	4	18	16	24	1

Figure 6.1: Sequences of Pipe replacement in different scenarios

6.1.1 User Oriented Scenario

Cost Optimization

In this scenario, an examination has been conducted regarding the total reduction of demand across all network nodes throughout the entire duration of the simulation. A total of 1000 simulation runs were conducted, each involving sequences subjected to optimization via the PBIL algorithm. The optimization outcomes are presented in the next page.

It is evident that through the optimization of sequences, the cumulative demand deficit has substantially decreased from 752 to 30 m^3. This reduction underscores the significant impact that replacing the pipes with the optimized sequence would have on mitigating demand reduction throughout the work.

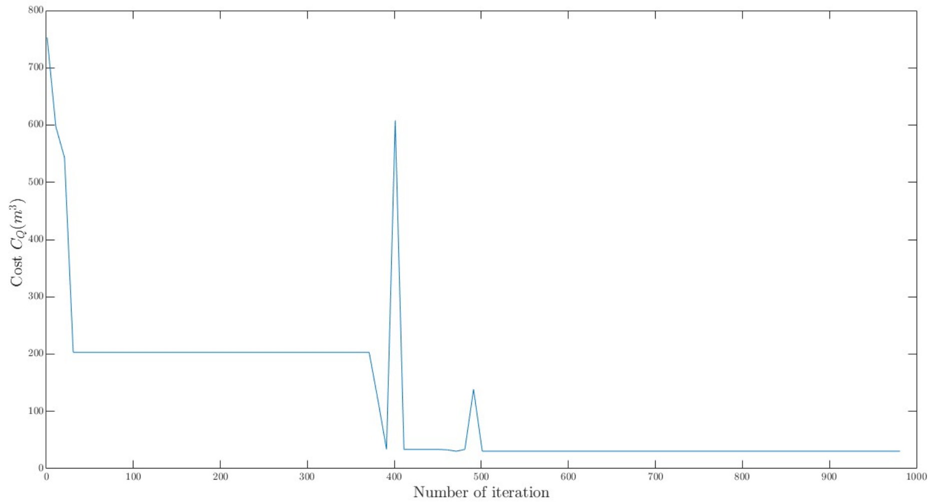


Figure 6.2: Cost Optimization; User Oriented Scenario

Robustness of Results

Assessing the impact of deviations from the optimized sequence, such as altering the replacement order of certain pipes, holds significance for both practical and theoretical considerations. Practically, this analysis sheds light on the adaptability of the schedule, offering insights into how adjustments can be made to accommodate unforeseen circumstances or constraints in real-world scenarios. Theoretically, it provides a means to evaluate the robustness and reliability of the optimized solution. By probing the effects of variations, we can gauge the solution's resilience to uncertainties and assess its validity in different contexts.
We compile statistics of the sequences J^* that are found during the NI iteration. It should be recalled that for each scenario (cost), NI = 1000, so the sample of J^* consists of 1000 sequences which are gradually ordered by the algorithm in the most efficient way. For each phase (m), we have a list of NI pipes that appeared in this phase. Through updates of the probability matrix of the algorithm, the likelihood of placing the pipe k in phase m increases toward obtaining the J^* sequence. Out of this dataset, it is possible to evaluate the number $N_{k,m}$ of times that the k-th pipe was replaced during the phase m. Dividing this number by NI, the frequency $B(k,m) = \frac{N_{k,m}}{NI}$ can be obtained. $B(k,m)$ takes values between 0 and 1, where the highest values indicate that pipe k must be changed in the sequence m to achieve

the minimum cost, while the average values suggest that pipe k could be or not be replaced in sequence m, and this has a minimum effect on the cost optimization. Finally, the lowest amounts of $B(k,m) = N_{k,m}$, around 0, indicate that the pipe k should never be replaced in sequence m, otherwise, it would increase the cost of optimization dramatically. The heat map of user oriented scenario sequences is shown below:

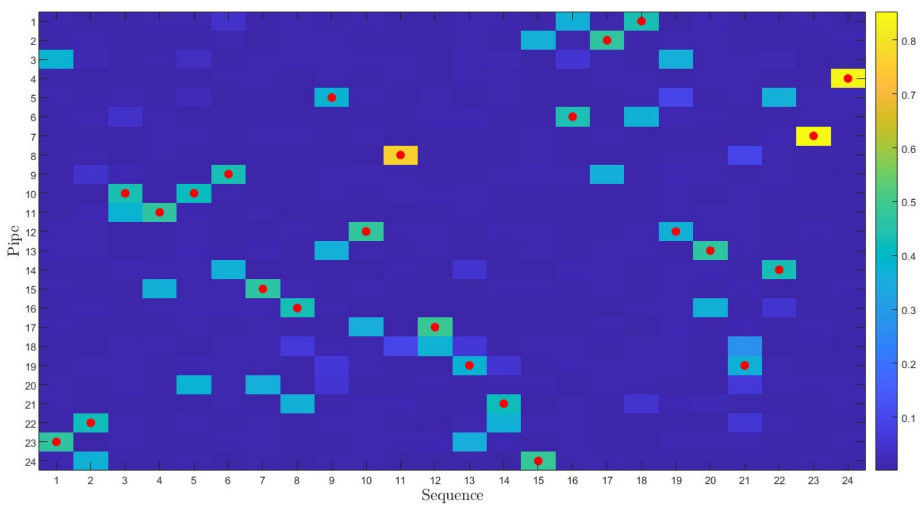


Figure 6.3: Heat map of Seqeces of replacement in User Oriented Scenario

The analysis reveals a correlation between the intensity of color heat in cells and the algorithm's preference for specific pipes replacement within each sequence. In sequence 1, for instance, pipe 23 exhibits the highest heat, suggesting its prioritization for replacement by the algorithm. Furthermore, the observation indicates that pipe 3 emerges as the second-most favored choice for replacement in this sequence, implying that substituting pipe 3 for pipe 23 would yield comparable outcomes with minimal impact on cost optimization.

Conversely, in sequence 23, the algorithm demonstrates a robust preference for replacing pipe 7. Consequently, altering this selection in favor of other pipes within the sequence would likely have a discernible effect on achieving the overarching objective of demand reduction during simulation.

Pressure in pipes during simulation

In addition, a comparative analysis of pipe pressure levels during the simulation has been conducted between the random and optimized sequences, as illustrated in below.

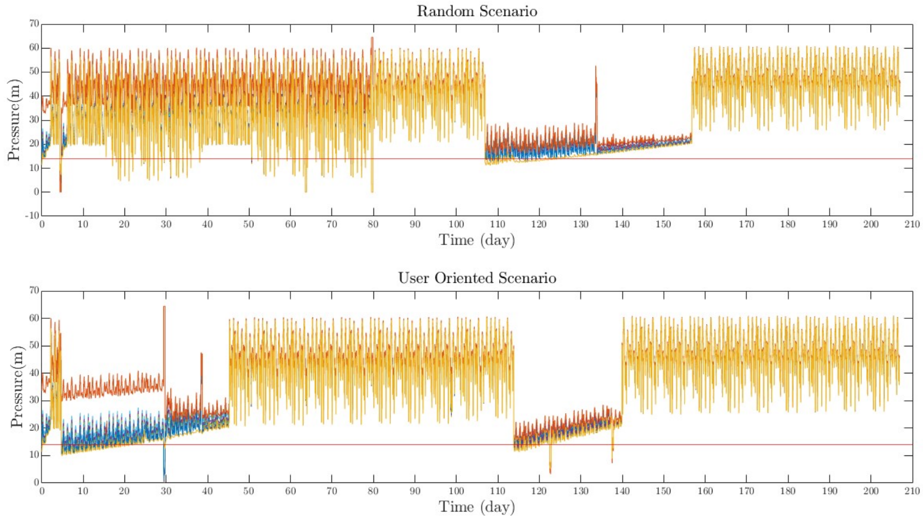


Figure 6.4: Pressure in nodes during simulation in Random and User oriented scenarios

It is evident that while the primary focus of the user-oriented scenario has been on mitigating demand reduction, it has also achieved a considerable level of success when compared to a random scenario in maintaining pressure levels above the minimum acceptable threshold, $P_{\text{min,j}} = 14$ m and in reducing pressure fluctuations.

Cumulative Demand reduction during simulation

Concerning the temporary closure of pipes for replacement, it is observed that the pressure in the adjacent nodes of the closed pipe decreases, resulting in a reduction in demand within the network. The cumulative demand reduction throughout the simulation is presented below.

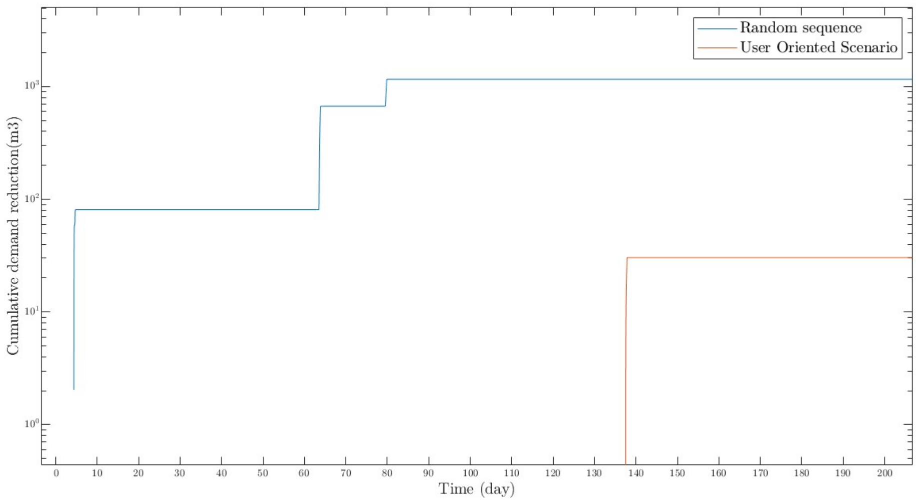


Figure 6.5: Cumulative demand reduction comparison between Random and User-Oriented scenarios

The efficacy of the User-Oriented Scenario in curtailing demand reduction during simulation is evident, with a notable decrease from 1100 m3 in the random scenario to a mere 30 m3, representing a optimization of more than 90 percent.

6.1.2 Compliance Oriented Scenario

Cost Optimization

In this scenario, an examination has been conducted regarding the total pressure deficit across all network nodes throughout the entire duration of the simulation. A total of 1000 simulation runs were conducted, each involving sequences subjected to optimization via the PBIL algorithm. The optimization outcomes are presented below.

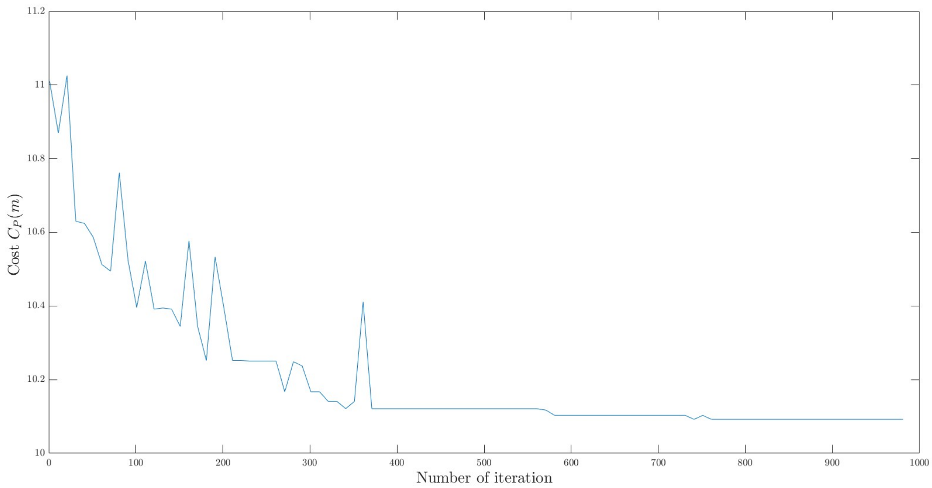


Figure 6.6: Cost Optimization; Compliance Oriented Scenario

It is evident that through the optimization of sequences, the cumulative pressure deficit has decreased from 11 to 10 m. This reduction underscores the impact that replacing the pipes with the optimized sequence would have on mitigating pressure reduction throughout the work.

Robustness of Results

As explained before, Robustness of results can be shown by heat maps. The heat map of Compliance oriented scenario sequences is shown below:

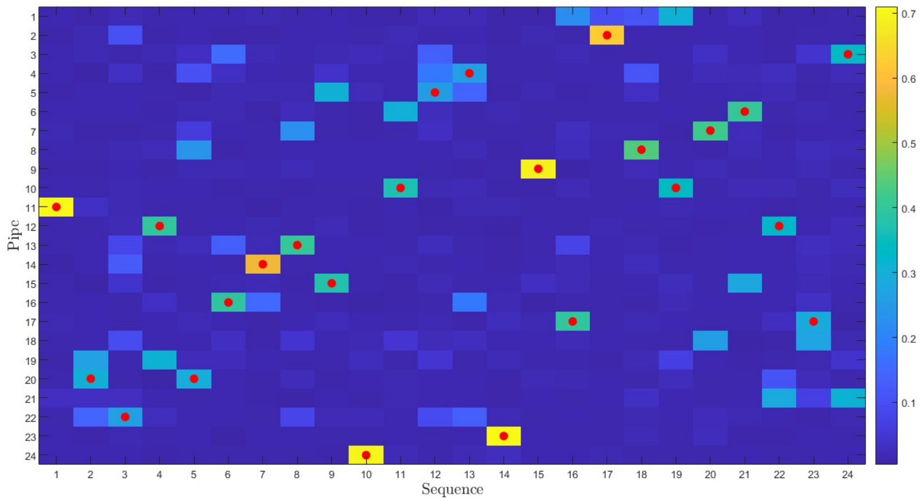


Figure 6.7: Heat map of Sequeces of replacement in Compliance Oriented Scenario

In sequence 2,pipe 20 exhibits the highest heat, suggesting its prioritization for replacement by the algorithm. Furthermore, the observation indicates that pipe 19 emerges as the second-most favored choice for replacement in this sequence, implying that substituting pipe 19 for pipe 20 would yield comparable outcomes with minimal impact on cost optimization.
Conversely, in sequence 1, the algorithm demonstrates a robust preference for replacing pipe 11. Consequently, altering this selection in favor of other pipes within the sequence would likely have a discernible effect on achieving the overarching objective of demand reduction during simulation.

Pressure in pipes during simulation

In addition, a comparative analysis of pipe pressure levels during the simulation has been conducted between the random and optimized sequences, as illustrated in the next page.
It is apparent that the Compliance-oriented scenario, with its principal objective of mitigating pressure reduction, has proven to be remarkably effective in sustaining

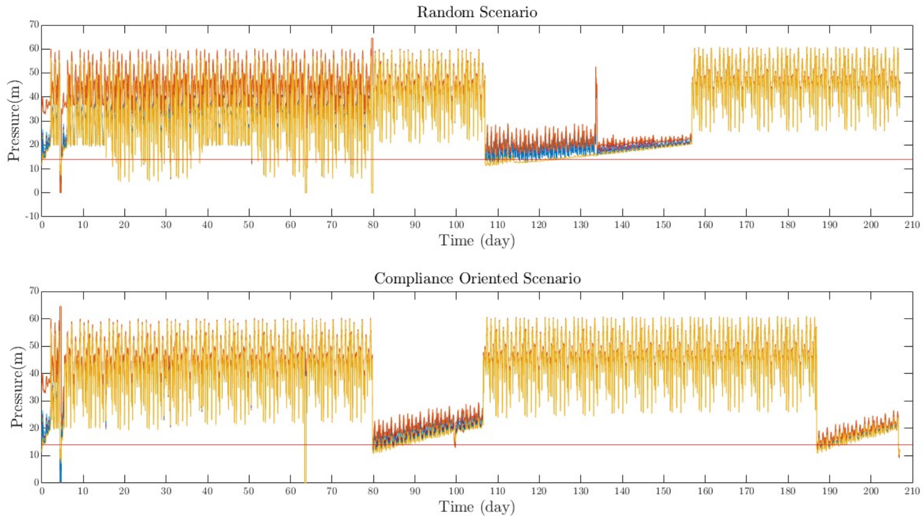


Figure 6.8: Pressure in nodes during simulation; Compliance Oriented Scenario

pressure levels above the minimum acceptable threshold, denoted as $P_{\text{min,j}} = 14$ m, while concurrently minimizing pressure fluctuations.

Cumulative Demand reduction during simulation

The cumulative demand reduction throughout the simulation has been assessed in two distinct scenarios: random and Compliance-oriented, the comparative results of which are presented next page.

The effectiveness of the Compliance-Oriented Scenario in mitigating demand reduction during simulation is inferior to that of the Service-Oriented Scenario. There is a decrease from 1100 m3 in the random scenario to 120 m3 in the Compliance-Oriented Scenario, which shows yet it remains significantly more efficient than the random sequence scenario.

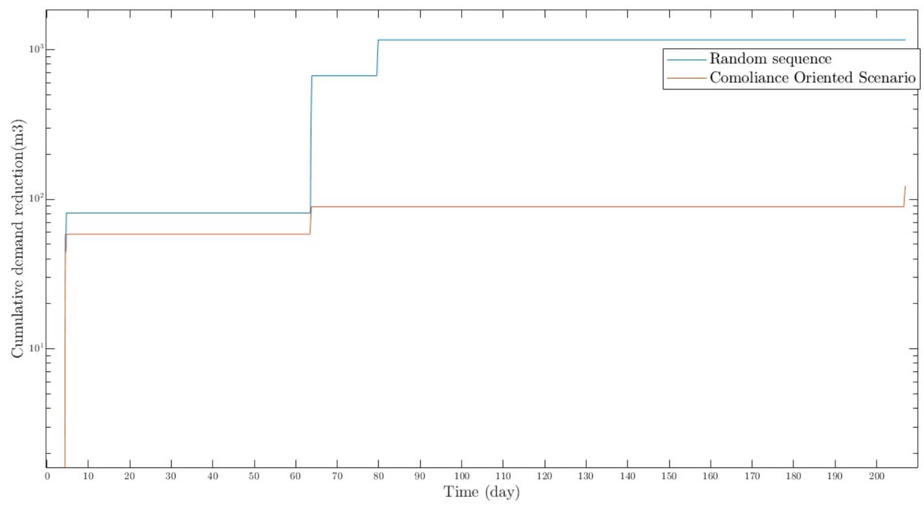


Figure 6.9: Cumulative demand reduction comparison between Random and Compliance-Oriented scenarios

6.2 C-Town Network

In this section, the results of simulations conducted on the C-Town model will be presented. These findings pertain to four distinct scenarios outlined below:

- User Oriented - Total demand deficit Scenario
- User Oriented - Relative demand deficit Scenario
- Compliance Oriented - Absolute pressure deficit Scenario
- Compliance Oriented - Relative pressure deficit Scenario

The random sequence of pipes replacement and the obtained User and Compliance sequences by the algorithm are shown below.

Random and Optimized Sequences of Pipe Replacement																													
Random Scenario						User Oriented Total demand deficit Scenario						User Oriented Relative demand deficit Scenario						Compliance Oriented Absolute Pressure deficit Scenario						Compliance Oriented Relative Pressure deficit Scenario					
Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe	Seq	Pipe
1	32	19	19	37	43	1	34	19	24	37	22	1	3	19	53	37	25	1	30	19	26	37	18	1	47	19	26	37	31
2	18	20	52	38	16	2	53	20	3	38	18	2	8	20	46	38	37	2	6	20	21	38	40	2	28	20	36	38	44
3	21	21	33	39	29	3	15	21	50	39	27	3	48	21	36	39	29	3	48	21	25	39	31	3	52	21	22	39	3
4	17	22	35	40	27	4	32	22	35	40	42	4	24	22	17	40	47	4	29	22	38	40	32	4	43	22	21	40	14
5	24	23	23	41	2	5	46	23	30	41	25	5	40	23	43	41	10	5	33	23	17	41	23	5	1	23	24	41	10
6	50	24	47	42	25	6	8	24	9	42	14	6	1	24	49	42	11	6	9	24	35	42	50	6	2	24	30	42	20
7	3	25	7	43	1	7	52	25	45	43	44	7	12	25	28	43	30	7	53	25	16	43	36	7	15	25	16	43	46
8	22	26	37	44	53	8	48	26	26	44	33	8	15	26	22	44	44	8	5	26	43	44	13	8	27	26	25	44	17
9	41	27	10	45	44	9	51	27	11	45	28	9	39	27	32	45	51	9	39	27	51	45	24	9	38	27	5	45	33
10	4	28	34	46	49	10	17	28	41	46	21	10	2	28	4	46	14	10	4	28	12	46	2	10	9	28	53	46	4
11	26	29	36	47	14	11	19	29	20	47	31	11	20	29	19	47	9	11	27	29	49	47	3	11	51	29	48	47	49
12	13	30	20	48	28	12	23	30	10	48	38	12	52	30	16	48	31	12	14	30	28	48	15	12	18	30	37	48	50
13	38	31	30	49	5	13	49	31	40	49	43	13	27	31	13	49	50	13	7	31	34	49	46	13	29	31	8	49	39
14	45	32	8	50	15	14	36	32	1	50	47	14	35	32	45	50	21	14	47	32	42	50	20	14	45	32	11	50	23
15	46	33	11	51	31	15	4	33	5	51	29	15	34	33	5	51	38	15	1	33	8	51	10	15	35	33	13	51	19
16	39	34	6	52	12	16	37	34	6	52	16	16	7	34	33	52	41	16	45	34	41	52	19	16	6	34	34	52	12
17	40	35	48	53	42	17	13	35	7	53	12	17	18	35	23	53	26	17	11	35	44	53	22	17	32	35	40	53	42
18	9	36	51			18	2	36	39			18	6	36	42			18	37	36	52			18	7	36	41		

Figure 6.10: Sequences of Pipe replacement in different scenarios

6.2.1 User Oriented - Total demand deficit Scenario

Cost Optimization

In this scenario, an examination has been conducted regarding the total reduction of demand across all network nodes throughout the entire duration of the simulation.

A total of 250 simulation runs were conducted, each involving sequences subjected to optimization via the PBIL algorithm. The optimization outcomes are presented below:

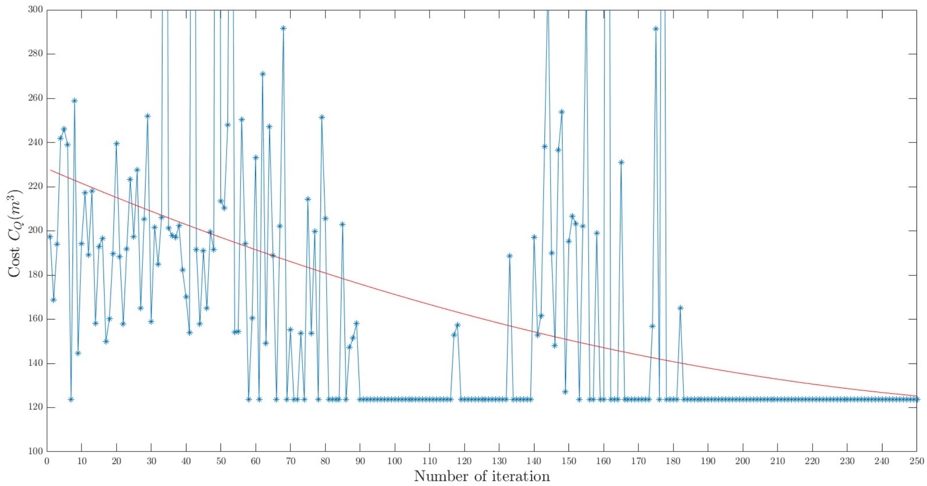


Figure 6.11: Cost Optimization;User Oriented - Total demand deficit Scenario

Through the optimization of sequences, the cumulative demand deficit has substantially decreased from highest 991 m^3 to lowest 123 m^3 (The data above 300 m^3 is not shown in the figure above). This reduction underscores the significant impact that replacing the pipes with the optimized sequence would have on mitigating demand reduction throughout the work.

Robustness of Results

As explained before, robustness of results can be shown by heat maps. The heat map of user oriented scenario sequences is shown in the next page.
The analysis reveals a correlation between the intensity of color heat in cells and the algorithm's preference for specific pipes replacement within each sequence. It is evident that within all sequences, the algorithm consistently makes robust selections. Any deviation from the optimized sequence is anticipated to exert a notable influence on the cost function, thereby affecting the total demand reduction value significantly.

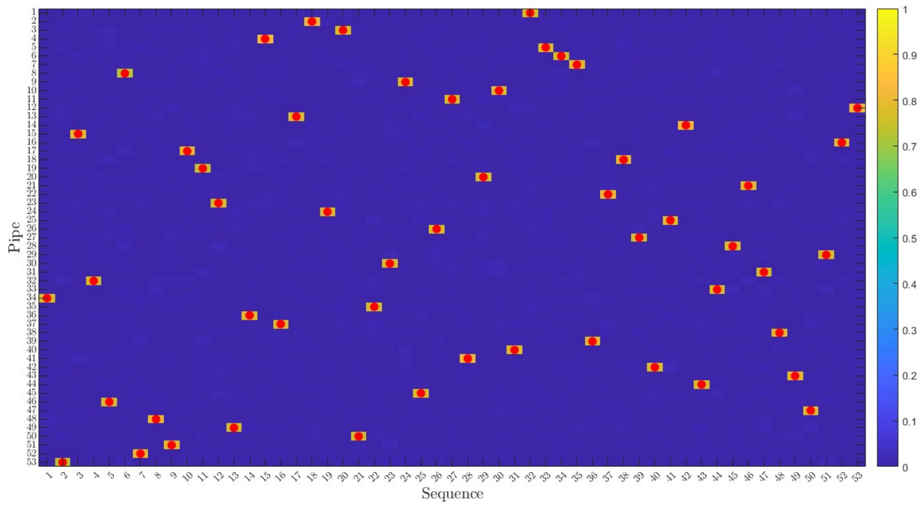


Figure 6.12: Heat map of Sequences of replacement in User Oriented total demand deficit Scenario

Pressure in pipes during simulation

In addition, a comparative analysis of pipe pressure levels during the simulation has been conducted between the random and optimized user oriented total demand deficit scenario. Two mentioned scenarios are compared as illustrated in the next page.
The User-oriented absolute demand deficit scenario appears to show a slightly less effective impact on maintaining pressure levels in junctions above the minimum acceptable threshold, $P_{\text{min,j}} = 35$, when compared to the random scenario. It is noteworthy to emphasize that the primary objective of this scenario has been focused on reducing demand reduction throughout the simulation.

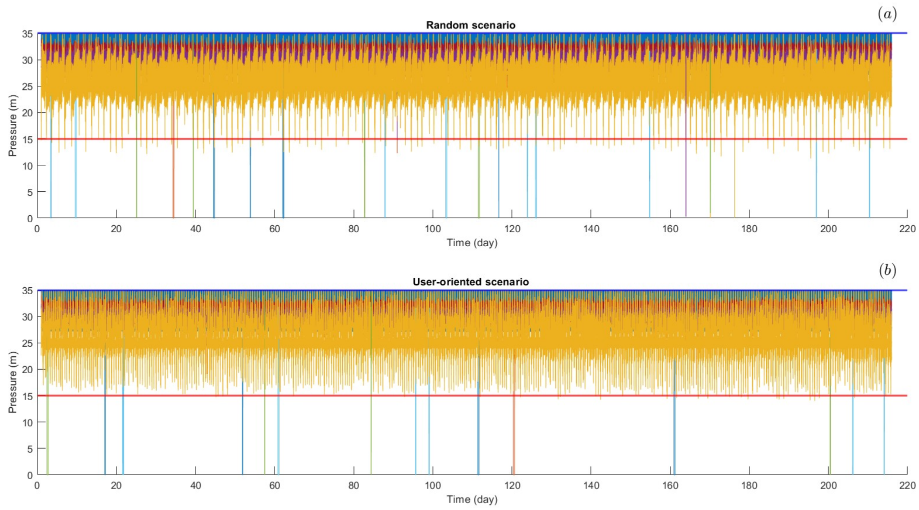


Figure 6.13: Pressure in nodes during simulation- Random and User oriented total demand deficit Scenario

Cumulative Demand reduction during simulation

Concerning the temporary closure of pipes for replacement, it is observed that the pressure in the adjacent nodes of the closed pipe decreases, resulting in a reduction in demand within the network.

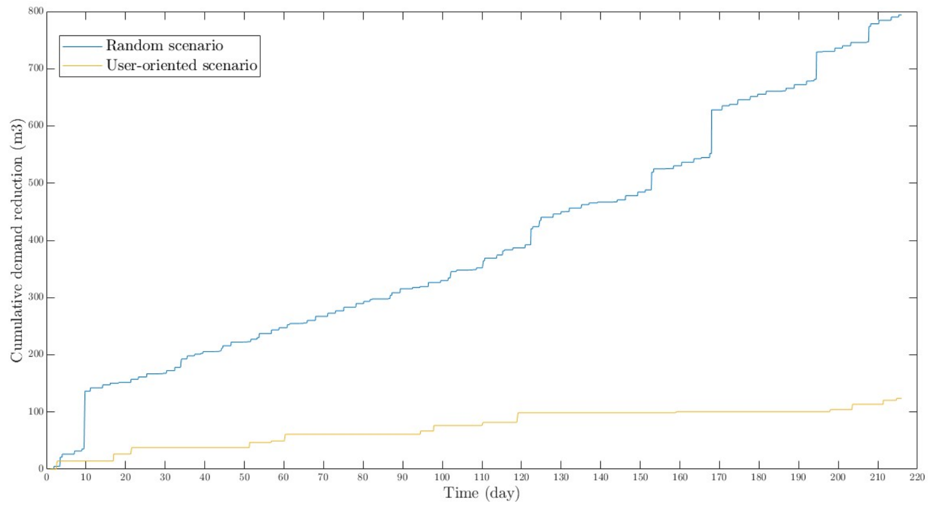


Figure 6.14: Cumulative demand reduction comparison between Random and User-oriented total demand deficit scenarios

The efficacy of the User-oriented scenario in curtailing demand reduction during simulation is evident, with a decrease from 794 m3 to 123 m3.

6.2.2 User Oriented - Relative demand deficit Scenario

Cost Optimization

In this scenario, an examination has been conducted regarding the relative reduction of demand across all network nodes throughout the entire duration of the simulation. A total of 250 simulation runs were conducted, each involving sequences subjected to optimization via the PBIL algorithm. The optimization outcomes are presented in below.

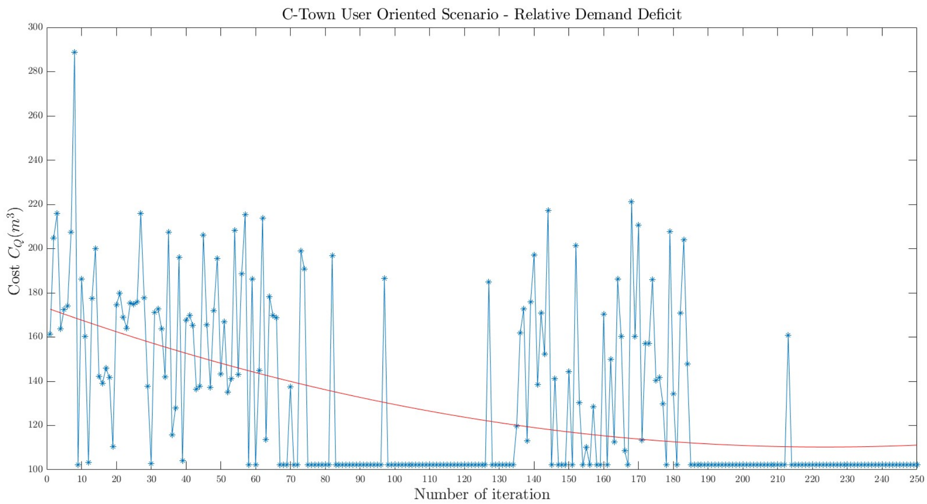


Figure 6.15: Cost Optimization;User Oriented - Relative demand deficit Scenario

It is evident that through the optimization of sequences, the relative demand deficit has substantially decreased from 285 to 101 m^3. This reduction underscores the significant impact that replacing the pipes with the optimized sequence would have on mitigating demand reduction throughout the work.

Robustness of Results

As explained before, Robustness of results can be shown by heat maps. The heat map of user oriented relative demand deficit scenario sequences is shown below:

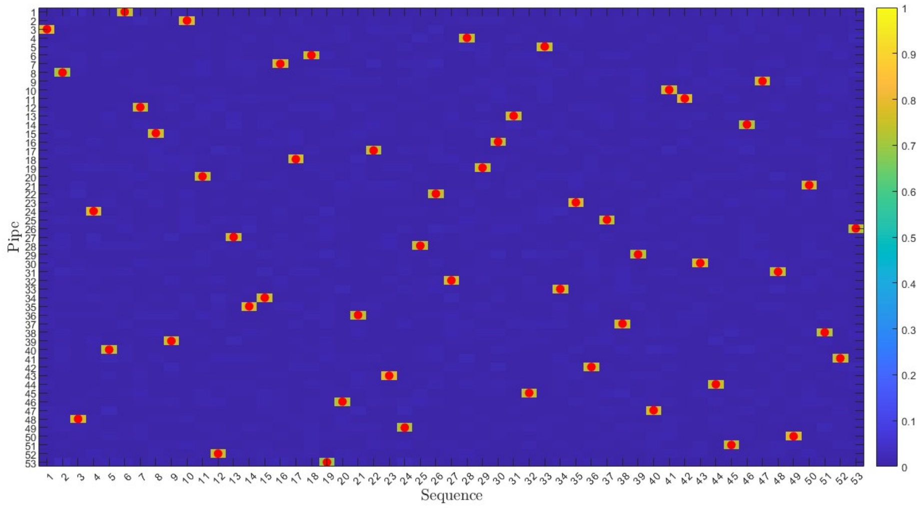


Figure 6.16: Heat map of Sequences of replacement in User oriented relative demand deficit Scenario

The analysis reveals a correlation between the intensity of color heat in cells and the algorithm's preference for specific pipes replacement within each sequence.
It is evident that within all sequences, the algorithm consistently makes robust selections. Any deviation from the optimized sequence is anticipated to exert a notable influence on the cost function, thereby affecting the total demand reduction value significantly.

Pressure in pipes during simulation

In addition, a comparative analysis of pipe pressure levels during the simulation has been conducted between the random and optimized User oriented relative demand deficit Scenario. To make the comparison the pressure during simulation between two mentioned scenarios is compared as illustrated in the next page.

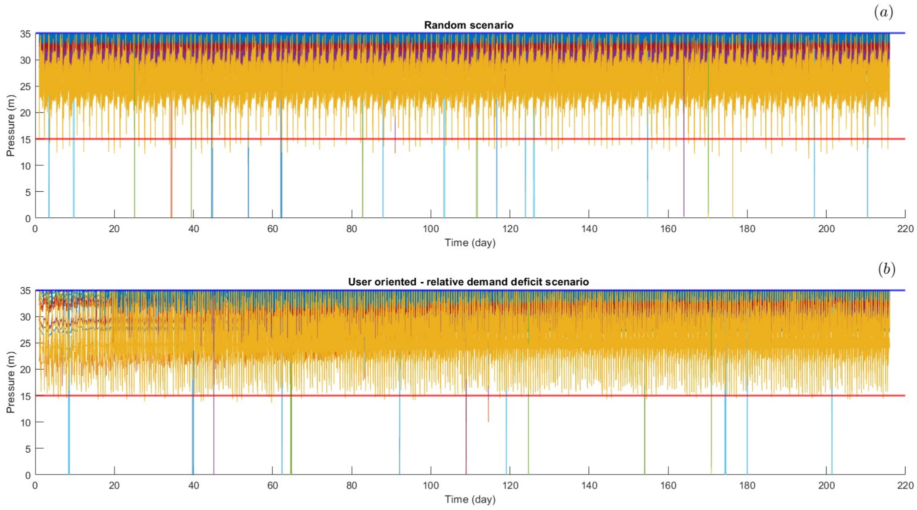


Figure 6.17: Pressure in nodes during simulation- Random and User oriented relative demand deficit Scenario

The user-oriented relative demand deficit scenario appears to demonstrate a slightly less effective impact on maintaining pressure levels in junctions above the minimum acceptable threshold, $P_{\text{min,j}} = 35.$, when compared to the Random scenario. It is noteworthy to emphasize that the primary objective of this scenario has been focused on reducing demand reduction throughout the simulation.

Cumulative Demand reduction during simulation

Concerning the temporary closure of pipes for replacement, it is observed that the pressure in the adjacent nodes of the closed pipe decreases, resulting in a reduction in demand within the network. The cumulative demand reduction throughout the simulation is presented below:

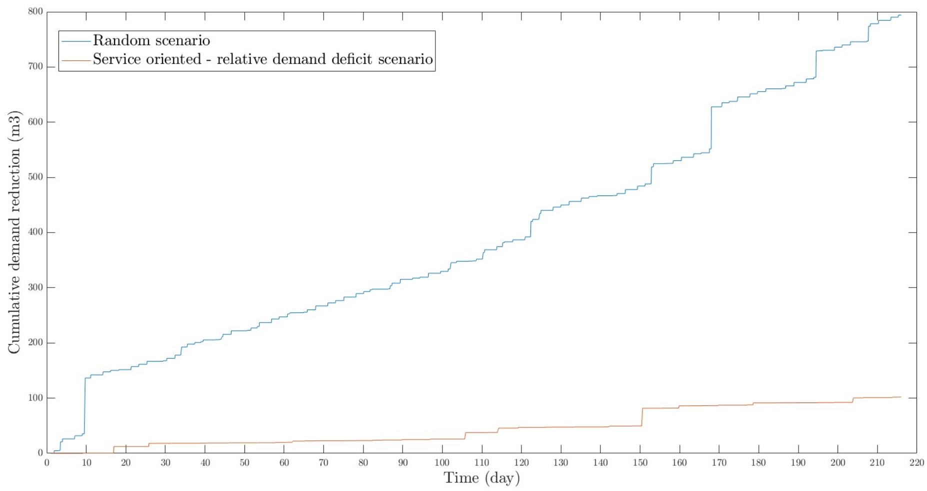


Figure 6.18: Cumulative demand reduction comparison between Random and User-oriented relative scenarios

The efficacy of the User-Oriented relative Scenario in curtailing demand reduction during simulation is evident, with a decrease from 794 m3 to 101 m3 .

6.2.3 Compliance Oriented - Total pressure deficit Scenario

Cost Optimization

In this scenario, an examination has been conducted regarding the total reduction of pressure below the minimum acceptable pressure $P_{\text{min,j}} = 35.$ across all network nodes throughout the entire duration of the simulation. A total of 250 simulation runs were conducted, each involving sequences subjected to optimization via the PBIL algorithm. The optimization outcomes are presented below:

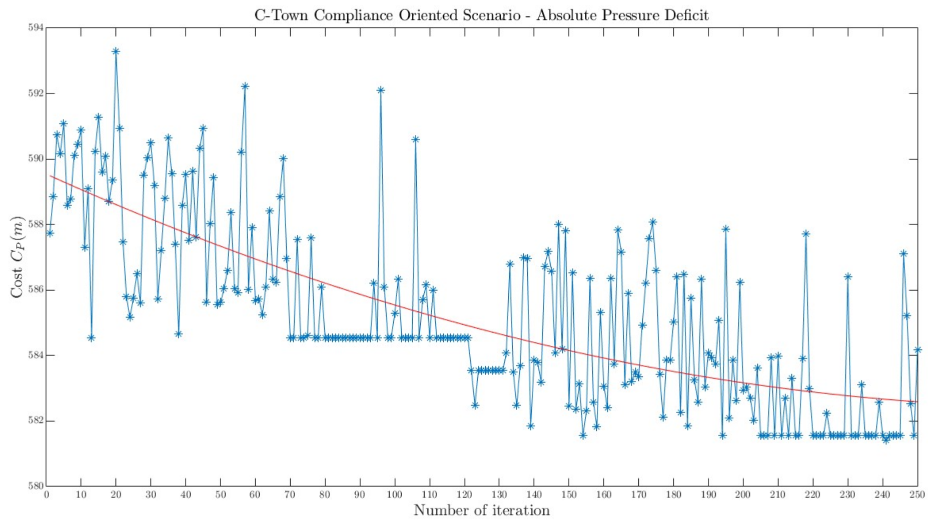


Figure 6.19: Cost Optimization;Compliance Oriented - absolute pressure deficit Scenario

It is evident that through the optimization of sequences, the cumulative pressure deficit has decreased from highest 593 m to lowest 581 m. This reduction underscores the minimal impact that replacing the pipes with the optimized sequence would have on mitigating pressure deficit throughout the work.

Robustness of Results

As explained before, robustness of results can be shown by heat maps. The heat map of Compliance oriented absolute pressure deficit scenario sequences is shown in the next page.

The analysis reveals a correlation between the intensity of color heat in cells and the algorithm's preference for specific pipes replacement within each sequence.

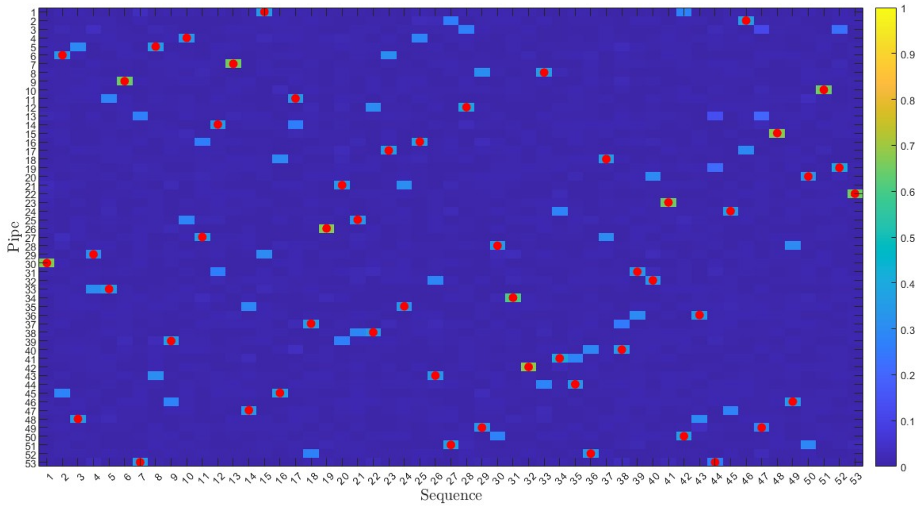


Figure 6.20: Heat map of Sequences of replacement in Compliance Oriented total pressure deficit Scenario

In sequence 1,pipe 30 exhibits the highest heat, suggesting its prioritization for replacement by the algorithm.The highest probability of heat in this sequence of pipes, denoted as Sequence 1, signifies that any deviation from the selected pipe within this sequence will exert a substantial impact on the project's cost, particularly in terms of pressure reduction.
Conversely, in certain sequences such as Sequence 24, the algorithm exhibits comparable probabilities of heat for two pipes, namely pipes 21 and 35. This suggests that altering either of these pipes would result in approximately equivalent impacts on the project's cost in terms of pressure deficit.

Pressure in pipes during simulation

In addition, a comparative analysis of pipe pressure levels during the simulation has been conducted between the random and optimized compliance oriented total pressure deficit Scenario. To make the comparison the pressure during of two mentioned scenarios during simulation is compared as illustrated below.

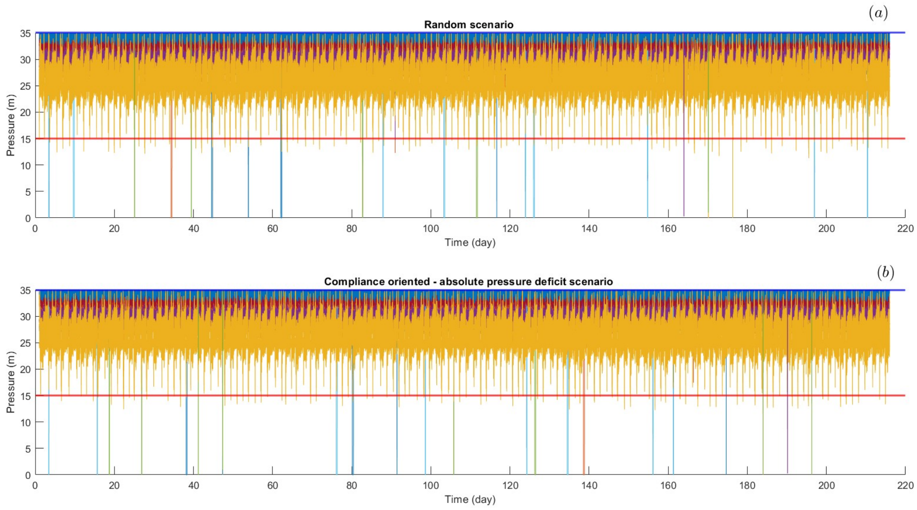


Figure 6.21: Pressure in nodes during simulation- Random and Compliance oriented absolute pressure deficit Scenario

The Compliance-oriented absolute pressure deficit scenario appears to have had minimal impact on maintaining pressure levels in junctions above the minimum acceptable threshold, $P_{\text{min,j}} = 35.$, when compared to the random scenario.

Cumulative Demand reduction during simulation

Concerning the temporary closure of pipes for replacement, it is observed that the pressure in the adjacent nodes of the closed pipe decreases, resulting in a reduction in demand within the network. The cumulative demand reduction throughout the simulation has been assessed in two distinct scenarios: random and Compliance-oriented absolute pressure deficit scenario, the comparative results of which are presented next page.

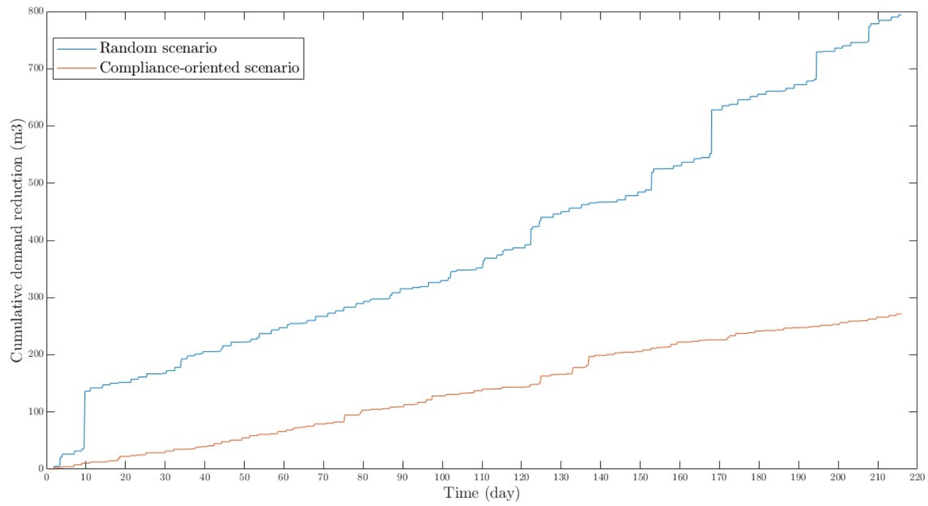


Figure 6.22: Cumulative demand reduction comparison between Random and Compliance-oriented absolute demand deficit scenarios

The efficacy of the Compliance-oriented absolute demand deficit scenario in curtailing pressure reduction during simulation is minimum, with a decrease from 794 to 271 m3.

6.2.4 Compliance Oriented - relative pressure deficit Scenario

Cost Optimization

In this scenario, an examination has been conducted regarding the relative reduction of pressure across all network nodes throughout the entire duration of the simulation. A total of 250 simulation runs were conducted, each involving sequences subjected to optimization via the PBIL algorithm. The optimization outcomes are presented below:

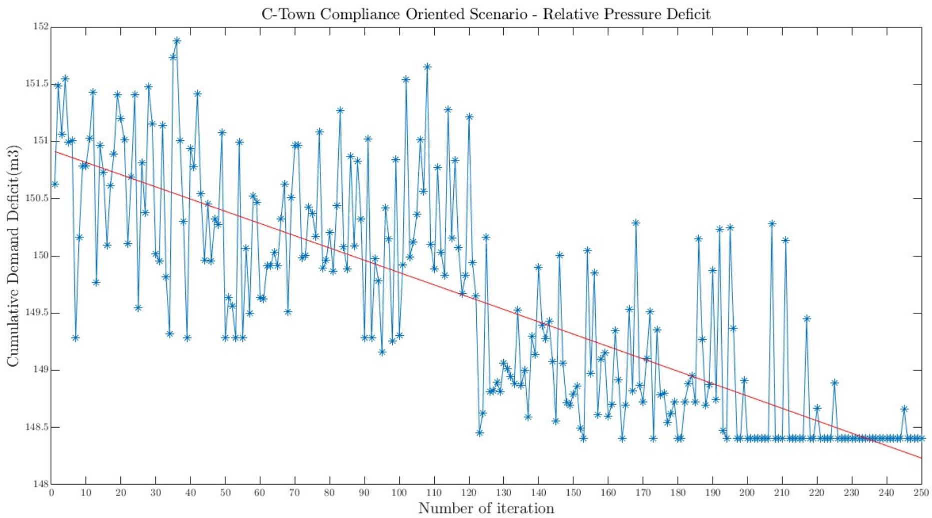


Figure 6.23: Cost Optimization;Compliance Oriented - Relative pressure deficit Scenario

It is evident that through the optimization of sequences, the relative pressure deficit has decreased from highest 151.8 m to lowest around 148.3 m. This reduction underscores the minor impact that replacing the pipes with the optimized sequence would have on mitigating pressure reduction throughout the work.

Robustness of Results

As explained before, Robustness of results can be shown by heat maps. The heat map of compliance oriented relative pressure deficit scenario sequences is shown below:

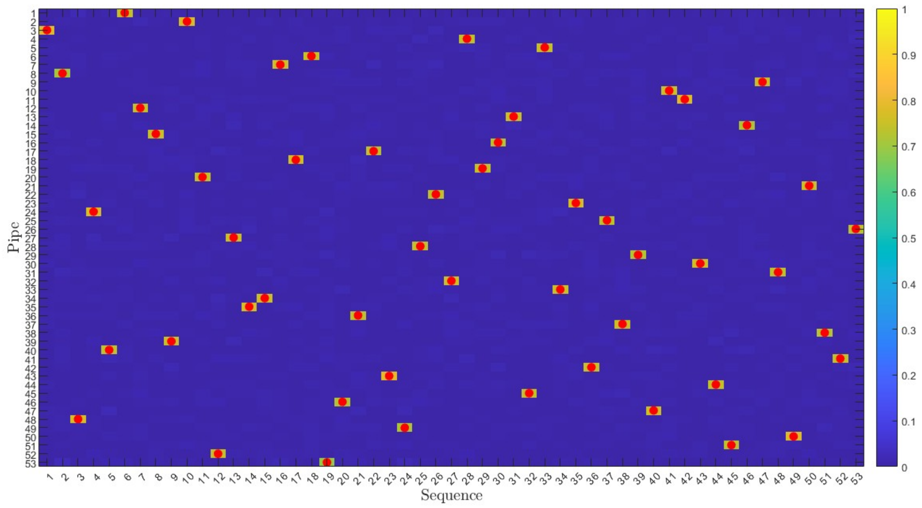


Figure 6.24: Heat map of Sequences of replacement in Compliance Oriented relative pressure deficit Scenario

The analysis reveals a correlation between the intensity of color heat in cells and the algorithm's preference for specific pipes replacement within each sequence.
The analysis reveals a correlation between the intensity of color heat in cells and the algorithm's preference for specific pipes replacement within each sequence. It is evident that within all sequences, the algorithm consistently makes robust selections. Any deviation from the optimized sequence is anticipated to exert a notable influence on the cost function, thereby affecting the total demand reduction value significantly.

Pressure in pipes during simulation

In addition, a comparative analysis of pipe pressure levels during the simulation has been conducted between the random and optimized Compliance Oriented relative pressure deficit Scenario. To make the comparison the simulation between two mentioned scenarios is compared as illustrated in the next page.

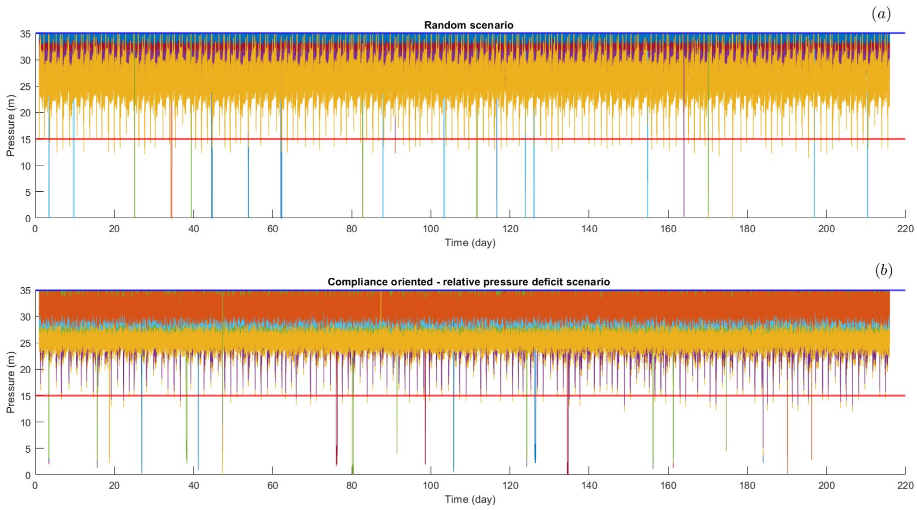


Figure 6.25: Pressure in nodes during simulation- Random and Compliance Oriented Relative pressure deficit Scenario

The Compliance-oriented relative pressure deficit scenario appears to have had minimal impact on maintaining pressure levels in junctions above the minimum acceptable threshold, $P_{\text{min,j}} = 35.$, when compared to the Random scenario.

Cumulative Demand reduction during simulation

Concerning the temporary closure of pipes for replacement, it is observed that the pressure in the adjacent nodes of the closed pipe decreases, resulting in a reduction in demand within the network. The cumulative demand reduction throughout the simulation has been assessed in two distinct scenarios: random and Compliance-oriented relative pressure deficit scenario, the comparative results of which are presented below.

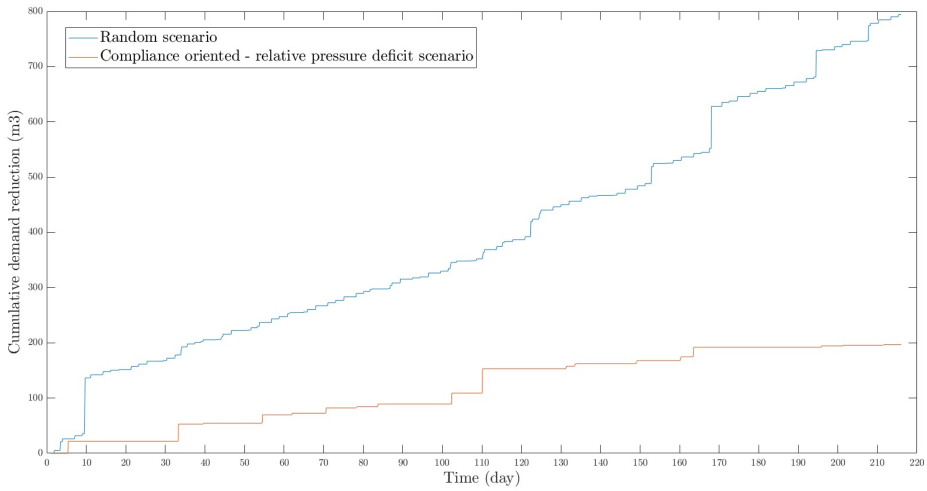


Figure 6.26: Cumulative demand reduction comparison between Random and Compliance-Oriented relative pressure deficit scenarios

The efficacy of the Compliance-oriented relative demand deficit scenario in curtailing pressure reduction during simulation is minimum, with a decrease from 794 to 199 m3.

6.3 Conclusion

In this thesis, a computational strategy for modelling the replacement of pipes in the context of network renovation has been presented. The strategy is based on the MATLAB's EPANet toolkit, that allows for the automatic modelling of a WDN with a time-varying topology, time-varying leakages, time-varying hydraulic characteristics of conduits. Such modelling strategy was adopted to find the optimal sequences of conduit replacement that can be implemented during renovation works of WDNs. In the context of this thesis, optimal means that the sequence of replacement minimizes a "cost". The costs that were considered in this work are scalar metrics that were derived from pressure time-series or junction's demand time-series. Different costs can be defined. In this thesis the focus was on: (i) a "user-oriented" (absolute and relative) cost, that measures possible problems related to customers satisfaction; and (ii) a "compliance-oriented" (absolute and deficit) cost, that measures possible problems related to the compliance of the water utility with minimum service standards. It was demonstrated that different sequences of pipe replacement impact to very different extents the users. It was also demonstrated that the optimization process led to significant and meaningful optimizations in simplified network and the well-known C-TOWN network.

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