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Automated Response Strategy and its Testbed Implementation for Contamination Management in Water Distribution Systems

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Ilmenau, 27.03.2024 Patricio José Flores Juárez

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Abstract

Access to clean drinking water is crucial worldwide. Throughout history, various methods of distribution have been developed to ensure that people have access to good quality water. Nowadays, there are various risks associated with water contamination, including those caused intentionally and unintentionally. Responding to such incidents typically involves manual decision-making processes, emphasizing the need for automated strategies.

This thesis introduces a novel approach employing Mixed Integer Nonlinear Programming (MINLP) to optimize isolation strategies and flushing methods within water distribution systems (WDSs). By integrating mass conservation and energy conversion equations, coupled with Hazen-Williams equation for pressure drop calculations, the proposed model aims to minimize contamination risks arising from various sources, including natural disasters and cyber-attacks.

The methodology undergoes validation and implementation through simulated benchmark scenarios to ensure its effectiveness and precision. Subsequently, real-world contamination scenarios are addressed within a practical testing environment (Testbed). Automation within the Testbed is achieved through the integration of software on a PC with Programmable Logic Controllers (PLCs).

Moreover, the study presents a comprehensive analysis of valve manipulation to mitigate contamination risks, alongside a comparison against scenarios without intervention. By automating response decisions and operational processes, the methodology showcases promising results in effectively managing contamination incidents within WDSs, thus offering a significant contribution to water system resilience and security.

Resumen

El acceso al agua potable es crucial en todo el mundo. A lo largo de la historia, se han desarrollado diversos métodos de distribución para garantizar que las personas tengan acceso a agua de buena calidad. Hoy en día, existen diversos riesgos asociados a la contaminación del agua, incluidos los causados intencionada y no intencionadamente. La respuesta a estos incidentes suele implicar procesos manuales de toma de decisiones, lo que pone de relieve la necesidad de estrategias automatizadas.

Esta tesis introduce un enfoque novedoso que emplea la programación no lineal entera mixta (MINLP) para optimizar las estrategias de aislamiento y los métodos de lavado en los sistemas de distribución de agua (WDS). Mediante la integración de las ecuaciones de conservación de masa y conversión de energía, junto con la ecuación de Hazen-Williams para los cálculos de caída de presión, el modelo propuesto pretende minimizar los riesgos de contaminación derivados de diversas fuentes, incluidos los desastres naturales y los ciberataques.

La metodología se somete a validación y aplicación mediante escenarios de referencia simulados para garantizar su eficacia y precisión. Posteriormente, los escenarios de contaminación del mundo real se abordan en un entorno de pruebas práctico (Testbed). La automatización dentro del banco de pruebas se consigue mediante la integración de software en un PC con controladores lógicos programables (PLC).

Además, el estudio presenta un análisis exhaustivo de la manipulación de válvulas para mitigar los riesgos de contaminación, junto con una comparación con escenarios sin intervención. Mediante la automatización de las decisiones de respuesta y los procesos operativos, la metodología muestra resultados prometedores en la gestión eficaz de incidentes de contaminación dentro de los WDS, ofreciendo así una contribución significativa a la resiliencia y la seguridad del sistema de agua.

Kurzfassung

Der Zugang zu sauberem Trinkwasser ist weltweit von entscheidender Bedeutung. Im Laufe der Geschichte wurden verschiedene Verteilungsmethoden entwickelt, um sicherzustellen, dass die Menschen Zugang zu Wasser guter Qualität haben. Heutzutage gibt es verschiedene Risiken im Zusammenhang mit der Verunreinigung von Wasser, einschließlich absichtlich oder unabsichtlich verursachter Risiken. Die Reaktion auf solche Vorfälle erfordert in der Regel manuelle Entscheidungsprozesse, was den Bedarf an automatisierten Strategien unterstreicht.

In dieser Arbeit wird ein neuartiger Ansatz unter Verwendung der gemischt-ganzzahligen nichtlinearen Programmierung (MINLP) zur Optimierung von Isolationsstrategien und Spülmethoden in Wasserverteilungssystemen (WDS) vorgestellt. Durch die Integration von Gleichungen zur Massenerhaltung und Energieumwandlung, gekoppelt mit der Hazen-Williams-Gleichung für Druckverlustberechnungen, zielt das vorgeschlagene Modell darauf ab, Kontaminationsrisiken zu minimieren, die aus verschiedenen Quellen stammen, einschließlich Naturkatastrophen und Cyberangriffen.

Die Methode wird durch simulierte Benchmark-Szenarien validiert und implementiert, um ihre Wirksamkeit und Präzision zu gewährleisten. Anschließend werden reale Kontaminationsszenarien in einer praktischen Testumgebung (Testbed) untersucht. Die Automatisierung innerhalb des Testbeds wird durch die Integration von Software auf einem PC mit speicherprogrammierbaren Steuerungen (PLCs) erreicht.

Darüber hinaus enthält die Studie eine umfassende Analyse von Ventilmanipulationen zur Minderung von Kontaminationsrisiken sowie einen Vergleich mit Szenarien ohne Eingriffe. Durch die Automatisierung von Reaktionsentscheidungen und Betriebsprozessen zeigt die Methodik vielversprechende Ergebnisse bei der effektiven Bewältigung von Kontaminationsvorfällen in Wasseraufbereitungsanlagen und leistet damit einen wichtigen Beitrag zur Widerstandsfähigkeit und Sicherheit von Wassersystemen.

Contents

Acronyms

WDS	Water distribution system
MINLP	Mixed integer nonlinear programming
PC	Personal computer
PLC	Programmable logic controller
WDN	Water distribution network
MILP	Mixed integer linear programming
NLP	Nonlinear programming
LPS	Liters per second
LPM	Liters per minute
GAMS	General Algebraic Modeling System
SCADA	Supervisory Control and Data Acquisition
OPC	Open Platform Communications

Symbols

i	Single node of the system
I	Set of nodes of the system
J	Set of pipes of the system
j	Single pipe of the system
$q_{in}(i)$	Incoming flows in node i
$q_{out}(i)$	Outgoing flows in node i
$D(i)$	Demand in node i
P_1, P_2	Pressure points of a system
u_1, u_2	Velocities at corresponding points within a system
h_1, h_2	Relative vertical heights within a system (m)
ρ	Density
g	Gravitational constant $(9,81\ m/s^2)$
q	Volumetric flow rate
L	Length of pipe
C	Pipe roughness coefficient
d	Inside pipe diameter
h_f	Head loss
n_0	Number of water sources
n_n	Number of nodes
n_p	Number of pipes
n_t	Number of nodes and water sources
p_i	Pressure in node i
P	Set of pressure in nodes of the system
q_j	Flow rate in the pipe j
Q	Set of flow rates of the system
v_j	Valve condition in the pipe j
d_i	Demand in the node i
D	Set of demands of the system
e_i	Elevation of the node i
E	Set of elevations of the nodes of the system
l_j	Length of the pipe j
L	Set of lengths of the pipes of the system

z_j	Diameter of the pipe j
Z	Set of diameter of the pipes of the system
x_i	Contamination level in the node i
X	Set of contamination levels in the nodes of the system
A_{out}	Adjacency matrix of outgoing flows
A	Adjacency matrix
M	Matrix for disabling Head Loss restriction
V_{p_j}	Availability of a valve in pipe j
V_p	Set of valves available in the system
$(h_{min})_i$	Minimum possible hydraulic head at node i
$(h_{max})_i$	Maximum possible hydraulic head at node i
Q_0	Set of initial flow rates
P_0	Set of initial pressures
V_0	Set of initial valve conditions
X_0	Set of initial contamination levels
R1, R2	Reservoirs of a case of study
P1, ..., P14	Pipes in case of study 1
N1, N2, ...	Nodes of a case of study
V1, V2, ...	Valves of a case of study
L1, ..., L11	Pipes in case of study 2
ZV1,ZV2	Filling valves of the Testbed
B1,B2	Water tanks of the Testbed
QI1, ..., QI4	Conductivity sensors of the Testbed
SV1, SV2, SV3	Contamination valves of the Testbed
AV1,..., AV8	Analog valves for demand of the Testbed
PI1, ..., PI5	Pressure sensors of the Testbed
FI1, ..., FI6	Water flow sensors of the Testbed
P1	Nomenclature for the clean water pump used in the Testbed
P2	Nomenclature for the polluted water pump used in the Testbed
Soll_P1	Clean water pump output level
AV7_FB	Valve AV7 opening percentage reading
t	Time

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Chapter I

Introduction

This chapter initiates with an exploration into the motivation for the topic selection. Subsequently, clear objectives are outlined to maintain focus and direction. Following this, the constraints and organizational structure of the thesis are elucidated, serving as a navigational guide for the reader. Finally, an examination of existing literature and prior research is conducted to provide context and insight into the broader field of study.

1.1 Motivation

Water Distribution Systems (WDSs) have been an important part of life of people since unmemorable times and the technology, nowadays, is trying to improve them in different aspects like keeping a steady and constant water pressure and water flow. Also, something really important is how to reach a proper level of water quality in order to prevent diseases, such as cholera, dysentery, hepatitis, typhoid, polio and others [2], from affecting people of a city or a community. And reaching this quality level is not the only aim but also to keep it through the whole system until it reaches the final user. There are numerous ways in which water within a system can compromise its quality, given the multitude of potential unauthorized access points within these systems [3].

Some points are situated in areas vulnerable to natural disasters, which, in the event of their occurrence, could potentially introduce contamination into the system. There are also some studies about malicious attacks where bacteria, protozoans and toxic chemicals may be introduced intentionally into the water systems, some others about cyberattacks that may cause disrupted operations. Even just vandalism or sabotage can cause contamination flow into the system [4]. In order to have a contingency plan for this unexpected contamination it is needed to be able to detect it and endeavoring, to the extent possible, to prevent the spread of this contaminated water flow within the system.

An optimisation technique can be used for the modelling of the WDSs [5] and the minimisation of the amount of contamination being introduced into the system. This thesis proposes and tests an approach in a simulated system and a physical test-bed.

1.2 Objectives

Throughout this thesis it will be shown how WDSs can be modelled mathematically using a MINLP approach [5]. Models for this systems can become complex due to non-linearities caused by pressure loss due to friction in the pipes, known as head loss, which is calculated using the Hazen-Williams equation. A water contamination reduction is intended to be achieved so an appropriate mathematical model will be developed and implemented using dedicated software for solving mathematical optimisation problems.

1.2.1 General Objective

The main objective of this thesis is to develop, implement and validate an MINLP model of a WDS that can improve the water quality therein by minimizing the contamination that is coming into the system due to different causes, intentional and unintentional as explained by [3] by opening and closing valves completely, these are our binary variables (v).

Firstly, MINLP models presented in [6], [7] and [8] are analysed in depth in a mathematical basis and the results are compared with the main objectives to be achieved in this thesis. Some approximations for the Hazen-Williams equation presented in [9] and [10] are taken in consideration and tested but not implemented. Based on this previous research, a model will be proposed that fits our objectives and parameters, For example, instead of the presence of a valve [8], where 1 means it is present and 0 otherwise, in our model the opening or closing of a valve is our main controllable parameter, where 1 means an ideally open valve and 0 otherwise. The GAMS software and the Bonmin solver[11], mentioned in [8] and [7], will be used to implement the proposed model, which will be tested in two simulated systems using the EPANET software.

In addition, one of the simulated systems is a test-bed implemented at the Technical University of Ilmenau by a former student as part of his master's thesis [12], so the final validation will take place in this real-world scenario and the results and conclusions will be presented.

1.2.2 Specific Objectives

In order to achieve the main objective, the following specific objectives have been set out

- To carry out an in-depth research of articles and technology reports in which the MINLP approach has been used for the optimisation of WDSs.
- To propose and implement a MINLP-type model based on previous research using the GAMS software and the Bonmin solver, considering the most appropriate approaches and relaxation methods to obtain a meaningful result.
- To implement two simulations of WDSs using the EPANET software. One of these sys-

tems will consider the parameters and characteristics of the real system in the laboratory of the Technical University of Ilmenau.

- To present results and conclusions on the validation of the model implemented in GAMS on the systems simulated in EPANET and on the real system in the laboratory.

1.3 Structure

This thesis will investigate past models and implement a MINLP model adapted to our needs. The model will be validated in two simulated systems and a real one. The results and conclusions will be presented in the final part. The structure of this thesis is as follows: Firstly, Chapter 2 is a presentation of the state of the art, the previous research and the implementation of the test-bed. Chapter 3 presents the methodology used to implement the model and algorithm. The case studies will be presented afterwards. These consist of two models simulated in EPANET, one of which is physically present in the laboratory and will also be introduced appropriately in Chapter 4. In Chapter 5, updates made to the test bench will be presented. This includes additions and changes to the software, allowing for complete remote control of the system. Finally, in Chapter 6, the results of the validation are presented, compared, and suggestions for future research proposed.

Chapter II

State of the art

Ensuring a safe and reliable drinking water supply requires effective water quality control in distribution systems. This chapter presents a review of the latest developments in monitoring, control, and optimisation technologies in this field.

The discussion covers traditional methods, limitations associated with manual monitoring, and conventional water quality control systems. The text presents recent developments in water quality management, including the use of smart sensors and automated control systems.

It also explores the application of optimisation techniques, such as the Mixed Non-Linear Programming (MINLP) method, in improving water quality in distribution systems. Relevant studies are reviewed that have utilized MINLP and other optimisation approaches to enhance efficiency and water quality in distribution systems are reviewed.

This state-of-the-art review provides a strong foundation for comprehending the context and significance of the research presented in this thesis on optimal water quality control in distribution systems.

2.1 Water quality control in WDS

Water quality control in distribution systems is a crucial aspect of managing drinking water supply. This section will address the fundamental importance of maintaining high standards of water quality at all stages of the distribution process, from the source to the consumer's tap [13].

Despite technological and regulatory advances, WDSs still face challenges in maintaining water quality. These challenges include microbiological [2], chemical, and physical contamination of water during transport through the distribution network, intentional and unintentional [4], as well as problems such as pipe corrosion and biofilm formation [14].

To detect pollution problems, monitoring stations [3] equipped with sensors dedicated to the different types of pollution mentioned above are required. These stations control the quality of the water that passes through them and reaches the end-users' homes. Contingency methods are necessary in case of contamination. It is important to act promptly, effectively, and efficiently.

According to Silva [15], water quality can be monitored in three different areas. The first focus of water quality monitoring is physical, which includes the parameters of color, temperature, and turbidity. Optical technologies are commonly used to monitor these parameters, with electrical methods being used for temperature in some cases. The chemical monitoring of water quality encompasses various parameters such as chlorine, dissolved oxygen, fluorine, metals, nitrogen, pH, phosphorus, and oxidation reduction potential. This area predominantly employs electrical measurements, but optical measurements also play a significant role. The final aspect is the biological monitoring of water quality, which is divided into two subcategories. The first subcategory is Algae and Cyanobacteria, where one of the primary techniques used is cell counting with optical microscopes. The second subcategory is Total Coliforms and Escherichia coli, for which the main rapid detection methods, according to the American Public Health Association [16], are based on radiometric, glutamate decarboxylase, electrochemical, gas chromatographic, colorimetric, and potentiometric techniques.

One of the significant improvements in water quality control has been the development and implementation of innovative monitoring and analysis technologies. This includes the use of advanced sensors and telemetry systems that enable real-time monitoring of various water quality parameters such as those mentioned above. These technologies offer real-time data that allow for a prompt response to pollution events and a deeper comprehension of water dynamics in distribution systems. Some of these technologies are mentioned in [17].

2.2 Optimising Water Quality Control

Optimisation is essential for effectively managing water quality control in distribution systems. This sub-section explores how optimisation approaches can enhance the efficiency of water monitoring, treatment, and management processes, thereby contributing to the protection and improvement of drinking water quality.

To comprehend the application of optimisation in water quality control, it is crucial to examine the fundamental principles and concepts of optimisation in WDSs. This involves formulating objectives and constraints, selecting design and control variables, and defining cost functions and performance criteria.

O.M. Awe [18] outlines the required elements of the WDS model as follows:

- Reservoir
- Tank
- Junction
- Pipe
- Pump
- Valves

The types of WDS configuration are also outlined:

- Serial
- Branched
- Looped
- Combined

Finally, the text presents the optimisation methods, which are divided into two categories: deterministic optimisation and metaheuristics (stochastic). Mala-jetmarova [1] conducted a review of 107 publications on the optimisation of WDSs. The graphic in Figure 1 was obtained from this review.

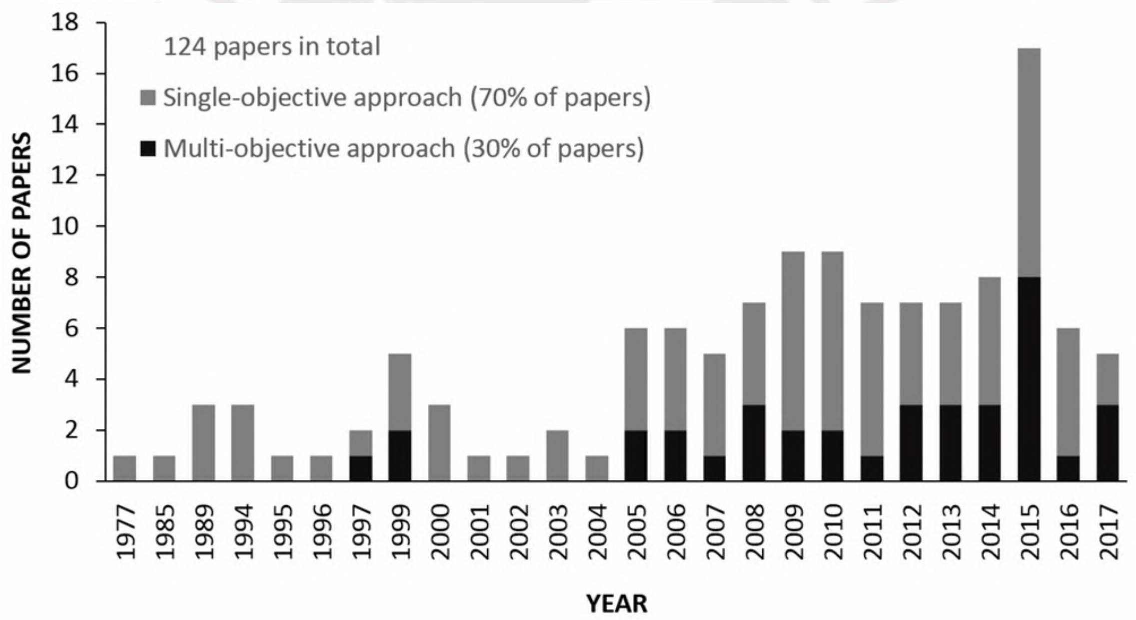

Figure 2.1: Optimisation methods by year [1]

The next subsection will also discuss another approach based on non-linear programming, including variations such as mixed-integer non-linear programming (MINLP), which is used in this thesis. The selection of the most appropriate method depends on the problem's complexity and specific optimisation objectives.

2.3 MINLP and application in WDSs

MINLP has emerged as a powerful tool in the optimisation of WDSs, allowing to efficiently address complex problems involving continuous and discrete variables. In this subsection, some of the most prominent applications of MINLP in the context of the design and operation of drinking WDSs will be explored.

Mixed-Integer Nonlinear Programming (MINLP) is a method for solving optimisation problems that involve both continuous and integer variables. It combines complexities from combinatorial (MILP) and nonlinear optimisation (NLP). MINLP has gained popularity over the past two decades, with contributions in theory, algorithms, and computation from a diverse community of engineers, mathematicians, and operations researchers [19]. The expression of a MINLP problem is conveniently shown in [20]:

$$\begin{cases} \underset{x}{\text{minimize}} & f(x) \\ \text{subject to} & C(x) \leq 0 \\ & x \in X \\ & x_i \in \mathbb{Z}, \quad \forall i \in I \end{cases} \tag{2.1}$$

where $f : \mathbb{R}^n \to \mathbb{R}$ and $c : \mathbb{R}^n \to \mathbb{R}^m$ are twice continuously differentiable functions, $X \subset \mathbb{R}^n$ is a bounded polyhedral set, and $I \subseteq 1, ..., n$ is the index set of integer variables. Note that it can easily include maximisation and more general constraints, such as equality constraints or lower and upper bounds $l \leq c(x) \leq u$ [20].

Sherali and Smith [6] present a model for determining the least-cost design of a network configuration to meet anticipated demand at acceptable pressure levels. The network consists of pipes that connect two nodes. These pipes can be divided into different segments, each of which adheres to commercial standards with specific values for diameter, roughness (Hazen-

Williams), and associated costs. To maintain the required pressure at the demand nodes, the design requires determining any additional head elevation (e.g. with the aid of pumps) that must be added to the system. The mathematical model and notation are presented in [6].

In 2009, Bragalli and D'Ambrosio [5] presented a practical model with a fixed topology using a continuous non-convex NLP relaxation and a MINLP search. The model aims to optimise the design of the water distribution network (WDN) by selecting the diameter of each pipe, which are pre-existing commercial values and cannot be modified. The objective function used in their study minimized the cost of the WDN:

$$\sum_{j \in J} C_j(diam(j))len(j) \tag{2.2}$$

Where:

J = Set of pipes

C_j = Cost function

$diam(j)$ = Diameter of pipe

$len(j)$ = Length of pipe $(j \in J)$

And the constraints would be the conservation of flow, which is linear, and the head loss across the links, which is non-smooth and non-convex.

More recently, Pecci [8] applied penalty and relaxation methods to the problem of optimal placement and operation of control valves in water supply networks. The complete optimisation problem is presented in (2.3):

$$\min \sum_{k=1}^{n_l} \frac{1}{W} \sum_{i=1}^{n_n} w_i p_i^k \tag{2.3a}$$

$$\text{subject to: } A_{12}^T q^k - d^k = 0, \quad \forall k = 1, \ldots, n_l, \tag{2.3b}$$

$$Q\left(q^k\right)\left(-A_{12}p^k - A_{12}e - A_{10}h_0^k - h_f\left(q^k\right)\right) \geq 0, \quad \forall k = 1, \ldots, n_l, \tag{2.3c}$$

$$-A_{12}p^k - A_{12}e - A_{10}h_0^k - h_f\left(q^k\right) - M^k z \leq 0, \quad \forall k = 1, \ldots, n_l, \tag{2.3d}$$

$$z_j + z_{n_p+j} \leq 1, \quad \forall j = 1, \ldots, n_p, \tag{2.3e}$$

$$\sum_{j=1}^{2n_p} z_j = n_v, \tag{2.3f}$$

$$p_{\text{min}}^k \leq p^k \leq p_{\text{max}}^k, \quad \forall k = 1, \ldots, n_l, \tag{2.3g}$$

$$0 \leq q^k \leq Q^{\max}, \quad \forall k = 1, \ldots, n_l, \tag{2.3h}$$

$$z \in \{0,1\}^{2n_p}, \tag{2.3i}$$

Where there are n_n nodes and n_p pipes and n_0 water sources, k is a time step, p are the pressure heads and q are the flows. As bidirectional positive flows are considered, there is a total of n_n + n_0 nodes and $2n_p$ links. The objective function (2.3a) is the minimisation of the average zone pressure at each demand scenario, w_i are just weights. (2.3b) is the conservation of mass law, (2.3c) and (2.3d) are the conservation of energy law where the head loss calculation makes it non-linear. (2.3e) and (2.3f) state that only 1 valve is allowed on each pipe, (2.3g) is to limit minimum and maximum pressure, (2.3h) is to ensure maximum flow and (2.3i) ensures that z (valve) is a binary variable, in this case 1 means a valve should be present.

Chapter III

Methodology

This chapter explains the methodology and final algorithm used for the tests. The explanation will provide a clear and concise account of the origin of the objective function and constraints, along with a mathematical and physical justification. The main objective is to isolate the contamination in order to prevent it to reach other places in the system

3.1 Hydraulic modeling of a WDS

To model the WDS, the mass and energy conservation equations in each node and link [21] are going to be used. In the first case, mass conservation, the flows that comes into a node have to be the same as the flows that goes out, including the demand (3.1)

$$q_{in}(i) - q_{out}(i) = D(i) \quad \forall i \quad \in \quad I \tag{3.1}$$

Where:

$q_{in}(i)$ = Incoming flows in node i

$q_{out}(i)$ = Outgoing flows in node i

$D(i)$ = Demand in node i

I = Set of nodes of the system

It is important to note that the demand is constant and does not depend on the pressure of the system; it is a fixed value.

The second important law is the conservation of energy, which introduces non-linearity to the model due to friction losses in the pipes. The starting point, however, is the well-known Bernoulli equation (3.2).

$$\frac{P_1}{\rho g} + \frac{u_1^2}{2g} + h_1 = \frac{P_2}{\rho g} + \frac{u_2^2}{2g} + h_2 \tag{3.2}$$

Where:

P_1 and P_2 = Pressure points of a system (Pa)

u_1 and u_2 = Velocities at corresponding points within a system (m/s)

h_1 and h_2 = Relative vertical heights within a system (m)

ρ = Density (kg/m^3)

g = Gravitational constant $(9,81\ m/s^2)$

Bernoulli's equation (3.2) ignores the effects of friction and can be simplified as follows: Pressure Energy + Potential Energy + Kinetic Energy = Constant. In fact, the following equation can be developed from the previous one, multiplying everything by 'ρg' and

$$P_1 + \rho g h_1 = P_2 + \rho g h_2 \tag{3.3}$$

To simplify and include friction losses, also known as head loss, the equation could be expressed as:

$$\Delta P + \Delta e = \Delta h_f \tag{3.4}$$

where h_f is the head loss, and all of these are expressed in meters of water column (mH_2O).

The Hazen-Williams equation (3.5) is used to calculate head loss in a pipe due to its simplicity and previous usage in relevant works, see [5], [8] and [6].

$$h_f = \frac{10.67q^{1.852}L}{C^{1.852}d^{4.8704}} \tag{3.5}$$

where:

$q =$ volumetric flow rate $(\mathrm{m^3/s})$

$L =$ length of pipe (m)

$C =$ pipe roughness coefficient

$d =$ inside pipe diameter (m)

$\mathrm{h_f} =$ head loss(m)

There is some research on possible approximations such as [22] and [23], but in this research they were only consulted as references, not implemented for the final tests cause it was not necessary.

These are the three main physics equations used to model any WDS. In the next section, the proper implementation for the MINLP problem of this thesis will be shown and explained.

3.2 The proposed MINLP problem

In this work, the model consists of n_0 water sources, n_n nodes, and n_p pipes. The sets I and J are constructed as follows:

$$
\begin{aligned}
i &\in I = \{1, ..., n_0 + n_n\} \\
j &\in J = \{1, ..., 2n_p\}
\end{aligned}
$$

The problem involves three main variables: the flow through pipes, denoted by $q_j \in Q$, the pressure in the nodes, denoted by $p_i \in P$, and the valves in a pipe, denoted by $v_j \in V$. The first two variables are considered positive values. The third variable, which is the main focus of this research, is a binary variable indicating whether a valve is open or closed. The variable v_j takes on values of either 0 or 1, where 1 indicates an open valve and 0 indicates a closed valve.

There are also some parameters like $d_i \in D$ and $e_i \in E$ which are the demand and the elevation of the node i respectively. Both of these are explicitly shown in the model. However, other parameters like the pipe length $l_j \in L$, $z_j \in Z$, and C which are the length, the diameter and the roughness coefficient of each pipe j, C is constant for all of them. From now on, let us consider $n_t = n_0 + n_n$. Finally, the minimization problem can be represented as follows:

$$\min \sum_{i=1}^{n_t} x_i A_{out} Q \tag{3.6a}$$

subject to: $A^T Q - D = 0,$ (3.6b)

$$q_j \left(-A(P-E) - h_{f_j} \right) \geq 0, \quad \forall j = 1, ..., 2n_p, \tag{3.6c}$$

$$-A(P-E) - h_{f_j} - M(1 - v_j) \leq 0, \quad \forall j = 1, ..., 2n_p, \tag{3.6d}$$

$$q_j + q_{n_p+j} = v_j(q_j + q_{n_p+j}), \quad \forall j = 1, ..., 2n_p, \tag{3.6e}$$

$$V_{p_j} + v_j \geq 1, \quad \forall j = 1, ..., 2n_p, \tag{3.6f}$$

$$v_j = v_{n_p+j}, \quad \forall j = 1, ..., 2n_p, \tag{3.6g}$$

$$q_j + q_{n_p+j} = 0, \quad \forall j = 1, ..., 2n_p, \tag{3.6h}$$

$$p_{\min} \leq p_i \leq p_{\max}, \quad \forall i = 1, ..., n_t, \tag{3.6i}$$

$$0 \leq q_j \leq q_{\max}, \quad \forall j = 1, ..., 2n_p, \tag{3.6j}$$

$$v_j \in \{0, 1\}^{2n_p}, \quad \forall j = 1, ..., 2n_p, \tag{3.6k}$$

The contamination at node i is denoted as $x_i \in X$ which is the set of contamination in the system nodes. The objective function seeks to minimise the sum of the flows leaving the polluted node.This can be calculated by multiplying the outflows by the level of contamination at the node and adding these values together. $x_i A_{out} Q$ (3.6a). The objective of this function is to minimize the contamination that goes out of the contaminated node and into the system. Note that contamination can still exit the node as a demand, which can be used for flushing. The matrix A_{out} is an adjacency matrix which considers only the adjacent pipes with outgoing flows of nodes and mark them as +1.

Equation (3.6b) is the mass conservation law, where the matrix $A^T \in R^{n_t x 2n_p}$ is the node-pipe adjacency matrix for the n_t nodes with the $2n_p$ pipes, where a +1 means the flow goes into the node, a -1 means the flows go out, and a 0 means there is no connection at all. Then the corresponding rows are equivalent to $\sum q_{in}(i) - \sum q_{out}(i) - D(i) = 0$

Inequalities (3.6c) and (3.6d) are the energy conservation equation, what both have in common is the multiplication $-A(P - E)$, where P and E are the pressure and height sets respectively. Solving this and subtracting h_f gives the simplified Bernoulli equation (2.1 Bernoulli). Now, in the case of (3.6c) it is multiplied by the flow q_j to disable this constraint when the flow q_j going through the pipe j is 0; and in the case of (3.6d) the matrix M multiplied by $(1 - v_j)$ is to disable it when the valve v_j in the pipe j is closed, so M must be a matrix with large enough values to achieve this. A minimun M is taken from [8], a way of choosing the values for M is shown. Given $i_1 \xrightarrow{j} i_2$, let $(h_{max})_{i_1}$ and $(h_{min})_{i_2}$ be the maximum and minimum possible hydraulic heads at nodes i_1 and i_2, respectively: $M_j := (h_{max})_{i_1} - (h_{min})_{i_2}$. In this model, the matrix M is multiplied by a weight that makes it larger. In a normal situation, where there is flow and the valve is open, the two inequalities become one $(\Delta p_i - \Delta e_i - h_f = 0)$

Equation (3.6e) is a constraint that forces the flow q_j to be 0 when the valve q_j is closed, the reason there is a sum of $q_j + q_{np+j}$ is because both pipes j and $n + j$ are the same, just the flows are in opposite directions it means one of them has to be 0. If the valve v_j is closed it means its value is 0, then the right part is 0 and the only way to make the left part 0 is to make q_j and q_{n_p+j} equal to 0. (3.6f) is quite simple, Vp is a vector that tells us if there is a valve in pipe j, in that case Vp_j is equal to 1, otherwise its value is 0. So if there is a valve in j, v_j can take any value $(0, 1)$, otherwise it must be 1 and act as an ideal open valve. The next equation (3.6g) is to make sure that the valve v_j is the same valve as v_{n_p+j}, because they are in the same pipe, just different flow directions.

The equation (3.6h) is a constraint that forces only one direction of flow in each pipe, to satisfy it q_j, q_{np+j} or both must be 0. The minimum and maximum of pressure and flow are defined by (3.6i) and (3.6j) respectively, and finally (3.6k) constrains v_j to be a binary value indicating whether a valve on a pipe is open or closed.

The initial flows Q_0, initial pressure P_0, initial valve conditions V_0 and initial contamination level X_0 must be specified for this mode. The head loss is calculated using the Hazen-Williams equation (3.5). For each different system, the remaining parameters are set. The solver employed in this work is BONMIN [11], as has been used in previous studies in this field [5], [8].

3.2.1 Improved model

The previous model enables the opening or closing of any valve in any order of priority, represents a problem for the pipe flushing logic. This logic will be explained in detail and also demonstrated in the testing section of this thesis in chapter 6,

To achieve a solution with valve priority to enable the proposed flushing logic, an additional restriction is imposed. To ensure a positive impact of this addition to the model, valves must be present in all pipes, or at least in those adjacent to the contaminated node. Otherwise, this restriction will be nullified. The objective is to give priority to closing the valves in the pipes adjacent to the contaminated node. The solver made an unintentional discovery that adding this constraint resulted in a faster solution compared to the original model.

$$A^T X \left(v_j \cdot V_{pj} \right) = 0, \quad \forall j = 1, ..., 2n_p \tag{3.7}$$

The result of the multiplication of $AT * X$ is the array of contaminated pipes, then if there is a valve installed in pipe j, V_{pj} will be 1, then to fulfil this constraint v_j must be 0. In summary, this restriction requires the closure of valves in pipelines adjacent to the contaminated node, if they exist.

The model is implemented using GAMS with the BONMIN solver. The solution will be tested in two simulated case studies using the EPANET software, followed by testing in a test bench available at the Technical University of Ilmenau.

Chapter IV

Case studies

This chapter provides a detailed explanation of the two case studies. Firstly, the EPANET simulated system will be discussed and second the simulated test bench system.

4.1 Case Study 1: Net4

The system consists of two reservoirs, R1 and R2, nine nodes (N1, N2, ..., N9), fourteen pipes (P1, P2, ..., P14) and twelve valves ($v_3, v_4, ..., v_{14}$). The following tables present the relevant data to test the model explained in the previous chapter.

Table 4.1 displays the elevations of the nodes and reservoirs in meters (m). This parameter is crucial for calculating energy conservation. Table 4.2 presents the diameter (in millimetres), length (in metres), and roughness coefficient C of the Hazen-Williams equation. These parameters are used to calculate the head loss using the equation mentioned earlier (3.5).

Figure 4.1 shows the complete schematic of the Net4 system in EPANET. Nodes 10 to 21 function as auxiliary nodes to position the valves correctly but are not considered in the model. The valves are treated as ideal, meaning there is no energy loss when they are open and they function as if they were not present.

	Elevation (m)
R1	100
R2	105
N1	90
N2	90
N3	90
N4	88
N5	88
N6	88
N7	85
N8	85
N9	85

Table 4.1: Elevations of Net4 nodes and reservoirs

	Diameter (mm)	Length (m)	Roughness Coeff. C
P1	300	1000	130
P2	300	1000	130
P3	300	1000	130
P4	300	1000	130
P5	300	1000	130
P6	300	1000	130
P7	300	1000	130
P8	250	1000	130
P9	250	1000	130
P10	250	1000	130
P11	250	1000	130
P12	250	1000	130
P13	200	1000	130
P14	200	1000	130

Table 4.2: Characteristics of Net4 Pipes

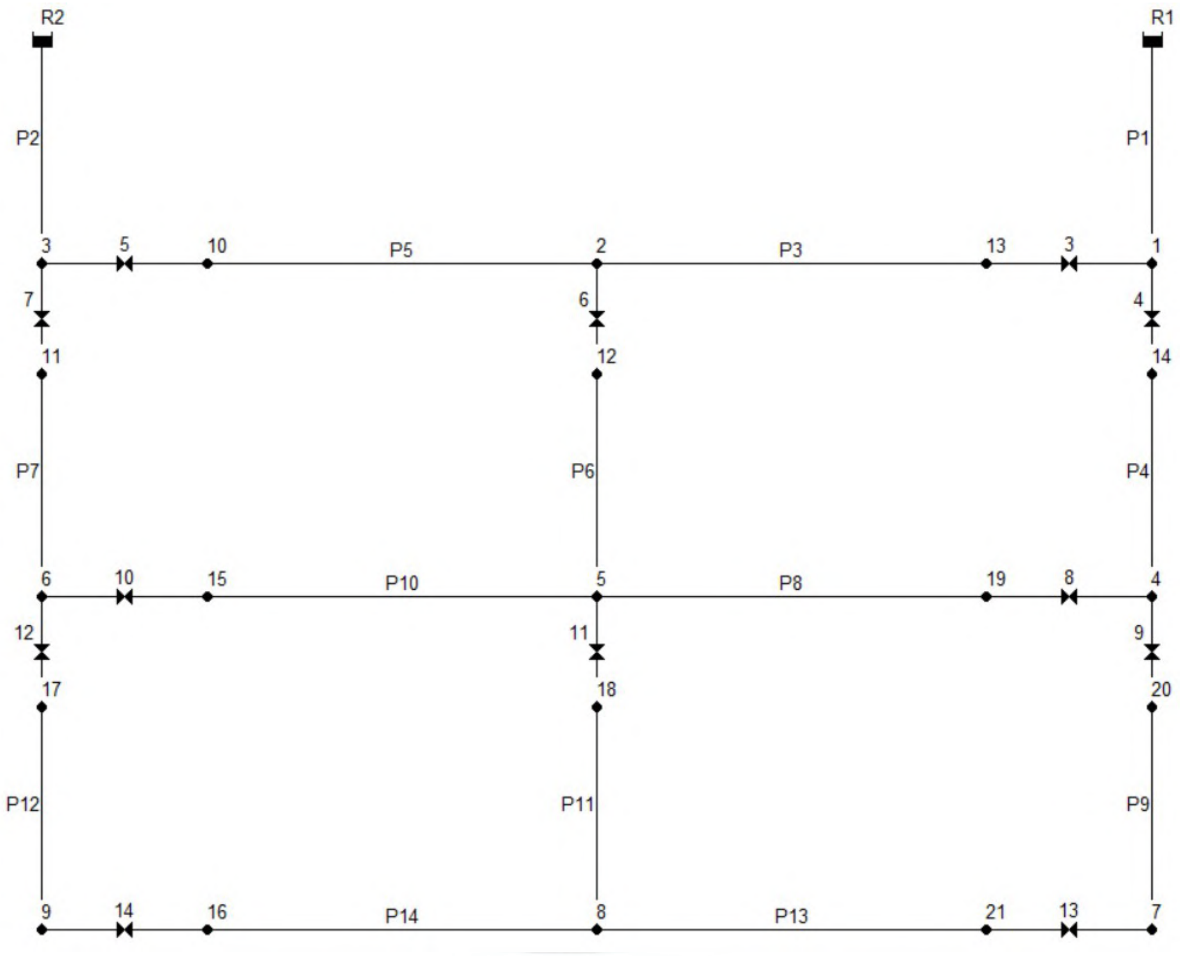

Figure 4.1: Net4 in EPANET

	Positive flow direction
P1	R1 $\longrightarrow$ N1
P2	R2 $\longrightarrow$ N3
P3	N2 $\longrightarrow$ N1
P4	N1 $\longrightarrow$ N4
P5	N3 $\longrightarrow$ N2
P6	N2 $\longrightarrow$ N5
P7	N3 $\longrightarrow$ N6
P8	N5$\longrightarrow$ N4
P9	N4 $\longrightarrow$ N7
P10	N6 $\longrightarrow$ N5
P11	N5 $\longrightarrow$ N8
P12	N6 $\longrightarrow$ N9
P13	N8 $\longrightarrow$ N7
P14	N9 $\longrightarrow$ N8

Table 4.3: Net4 Positive flow direction

It is important to consider the direction of flow, which is why Table 4.3 shows the direction of positive flow in each pipe. It is important to remember that our model considers two sets of positive flow pipes. In summary, the flow is positive from left to right and from top to bottom.

In the following subsections, the testing scenarios will be explained and the results will be presented.

4.1.1 Scenario 1

In this scenario, the system has all its valves available for modification, but there is only demand in three nodes. The demand for this is fixed and constant over time, and it is not affected by pressure. More details are provided in Table 4.4.

To start the test, it is essential to provide the MINLP problem with the initial values of the system when the contamination sensor indicates a risk level. Therefore, the simulation is run with these initial parameters to obtain the initial water flows (Q_0) and pressures (P_0). The initial valve positions (V_0) are already known and must be provided to the algorithm.

	Demand (LPS)
N1, ... , N6	0
N7	25
N8	25
N9	50

Table 4.4: Demands in Scenario 1 of Net4

Figure 4.2 shows the simulation results, displaying the initial flows and directions in a blue colour scale, as well as the initial pressure in the nodes in a red colour scale.

To run the solver with the model (3.6), it is necessary to create the matrices A, A_{out}, V_p and M, in this case $A \in R^{28\text{x}11}$, $A_{out} \in R^{11\text{x}28}$, $V_p \in R^{28}$ and $M \in R^{28}$. Since there are no valves in pipes P1 and P2, $V_{p_1} = V_{p_2} = V_{p15} = V_{p16}$ = 0, the rest is equal to 1.

For this scenario, the contamination sensor value was read at node 2 $(x_2 = 2)$. However, the value of contamination is not relevant.

4.1.1.1 Results for Scenario 1 of Net4

This subsection presents and analyses the results obtained for Scenario 1 of Case Study 1 using the MINLP method (3.6) described in the previous section.

After inputting the initial values as shown previously, the solver took 1 minute and 7.144 seconds to find a solution. The objective function value is $-2.8e^{-10}$, and the Table 4.5 displays the new valve positions.

v_3	v_4	v_5	v_6	v_7	v_8	v_9	v_{10}	v_{11}	v_{12}	v_{13}	v_{14}
0	1	1	0	1	1	1	1	1	1	0	1

Table 4.5: New valve values for Net4 Scenario 1

Due to the extremely low value of the objective function, it can be assumed that it is equal to 0. Therefore, it can be interpreted that there is no polluted flow exiting the system through any of the pipes connected to node 2. In other words, the flows $q_3, q_5, q_6, q_{17}, q_{19}, q_{20} = 0$. If there is demand in this contaminated node, then flow must go through one of the mentioned pipes. In

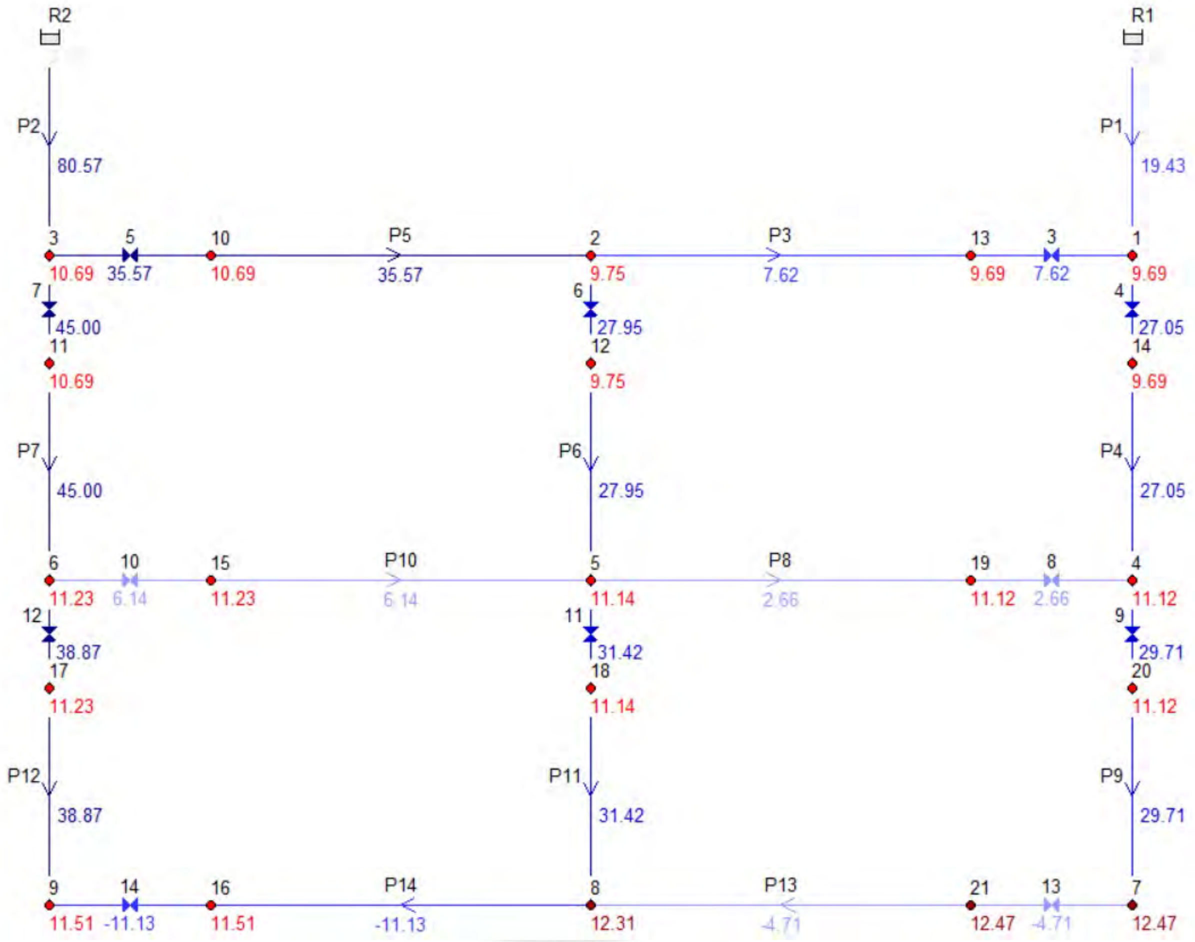

Figure 4.2: Initial values for Scenario 1 of Net4.

this specific case, it would be P5. As shown in Table 4.5, v_5 is still open, and the reason there is no water flow through it is because there is no demand. This is due to the mass conservation restriction (3.6b).

4.1.1.2 Validation of the results for Scenario 1 of Net4

This subsection presents the validation of the previously obtained results for this scenario in Net4. The validation will be performed through simulation in EPANET. The valve values will be changed, and the new system values will be analyzed.

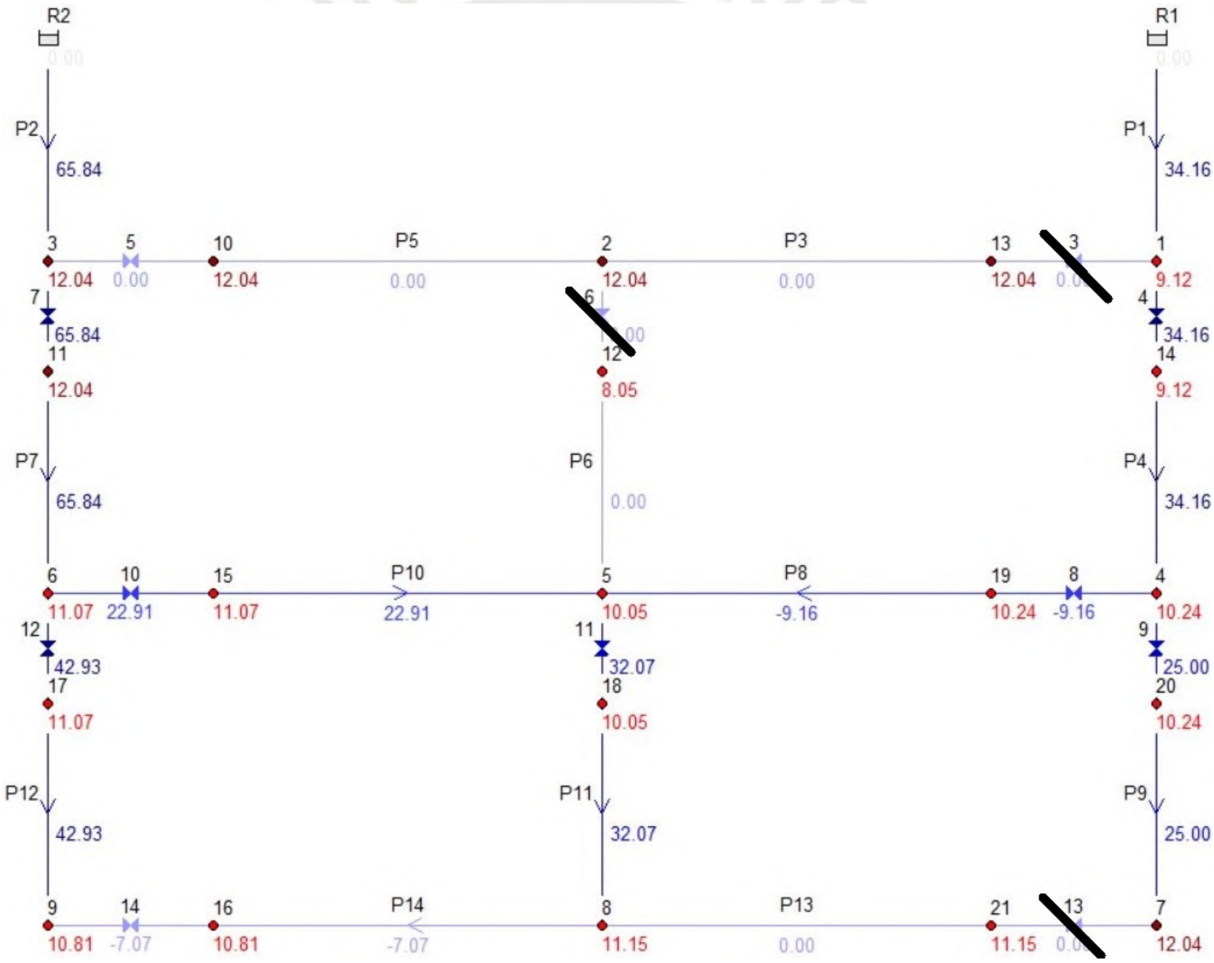

Figure 4.3: Validation of the results for Scenario 1 of Net4

Figure 4.3 illustrates that there is no water flow in the pipes connected to the contaminated node, due to the closed valves v_3 and v_6. Although there is no visible change in the simulated system valve figures, it can be inferred due to the pressure change in the nodes around the valve. In the case of an open valve without flow (v_5), the pressure remains constant in both nodes surrounding it (n_3, n_10); v_{13} has also been changed to closed, but this change is irrelevant in this scenario as it does not affect whether the demands have been met.

Thanks to this simulation, it can be stated that the model (3.6) achieves its intended purpose.

4.1.2 Scenario 2

In this second scenario, the contaminated node will be changed to node 4, meaning $x_4 = 2$ and $x_2 = 0$. All initial values remain the same as in scenario 1. The results are presented below.

4.1.2.1 Results for Scenario 2 of Net4

This subsection presents and analyses the results obtained for Scenario 2 of Case Study 1 using the MINLP method (3.6) described in the previous section.

After inputting the initial values as shown previously, the solver took 54.605 seconds to find a solution. The objective function value is $-3.23e^{-10}$, and the Table 4.6 displays the new valve positions.

v_3	v_4	v_5	v_6	v_7	v_8	v_9	v_{10}	v_{11}	v_{12}	v_{13}	v_{14}
1	0	1	1	1	0	1	0	1	1	1	0

Table 4.6: New valve values for Net4 Scenario 2

As in the previous scenario, the objective function value can be assumed to be 0 here as well. This is because contamination occurs in node 4, where there is no demand ($d_4 = 0$), resulting in all flows in the adjacent pipes being 0 ($q_4, q_8, q_9 = 0$).

4.1.2.2 Validation of the results for Scenario 2 of Net4

This subsection presents the validation of the previously obtained results for the second scenario in Net4. The validation will be performed through simulation in EPANET. The valve values will be changed, and the new system values will be analyzed.

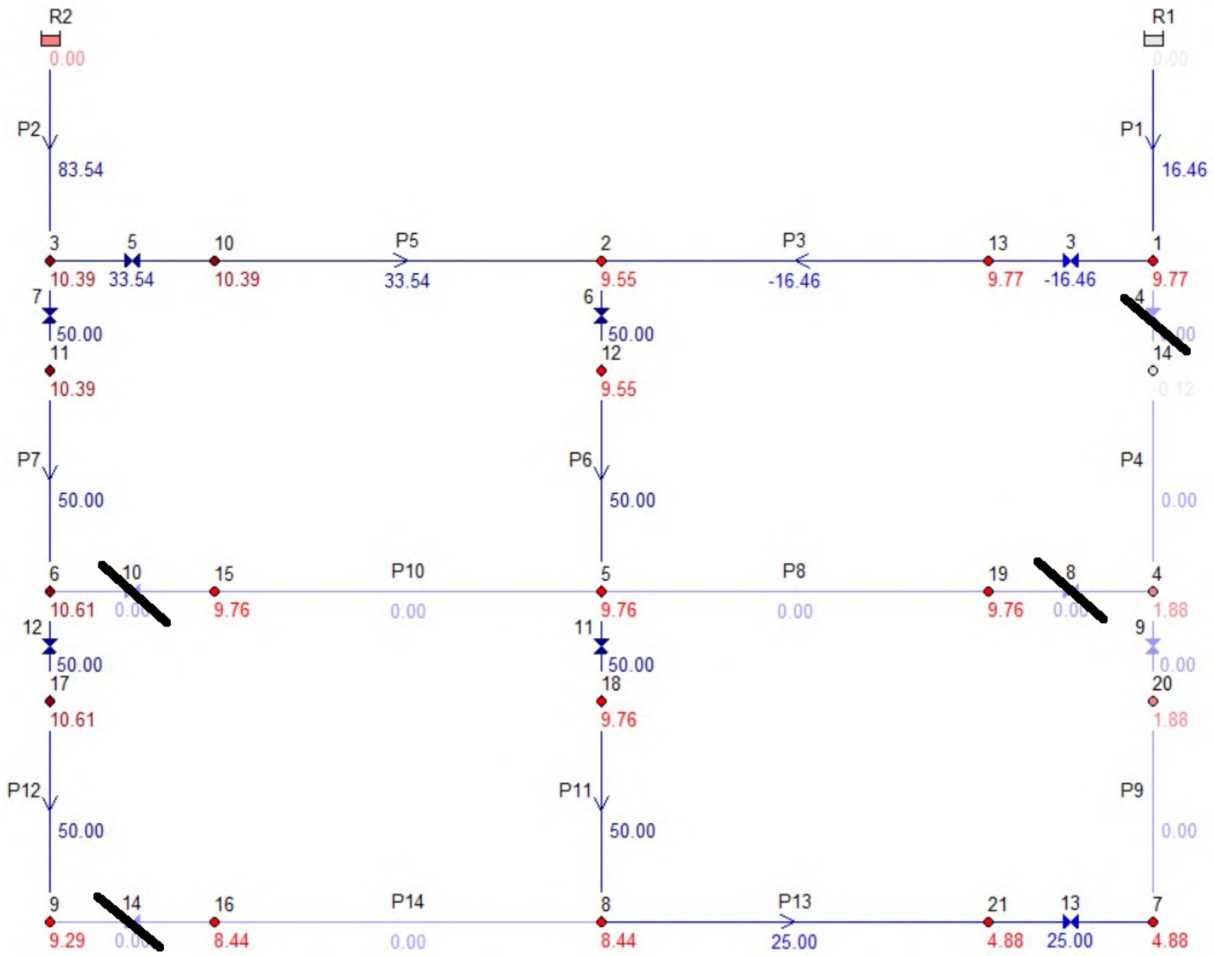

Figure 4.4: Validation of the results for Scenario 2 of Net4

In this scenario, it is evident that closing two valves is sufficient to prevent contamination from spreading into the system. However, it is important to note that the contamination does not enter as a flow of water, but as a mass that mixes with the existing flow of water in the system. If the contamination were to enter as a flow, it could potentially travel through p_9 towards the demand at node 7, given that the pressure is 0.

The algorithm also closed valves v_{10} and v_{11}, although it appears unnecessary. However, this is a characteristic of the MINLP model, which has multiple points with the same minimum level of the objective function.

4.1.3 Scenario 3

In this scenario, only one parameter will be changed: valve availability. To achieve this, the V_p array will be modified as shown in Table 4.7.

V_{p1}	V_{p2}	V_{p3}	V_{p4}	V_{p5}	V_{p6}	...	V_{p14}
0	0	1	0	1	1	...	1

Table 4.7: Valve availability for scenario 3

All the other initial values remain the same as in scenario 2. The results are presented below.

4.1.3.1 Results for Scenario 3 of Net4

For this scenario, the results are consistent with the previous ones, as expected. Table 4.8 shows the new valve arrangements in detail.

After inputting the initial values as shown previously, the solver took 34.34 seconds to find a solution. The objective function value is $-10.23e^{-10}$.

v_3	v_4	v_5	v_6	v_7	v_8	v_9	v_{10}	v_{11}	v_{12}	v_{13}	v_{14}
1	1	1	1	1	0	0	0	1	1	1	0

Table 4.8: New valve values for Net4 Scenario 3

In this scenario, v_4 is kept open as V_{p_4} is 0 and V_4 must be 1 to comply with constraint (3.6f). And instead of this, v_9 is closed. This should be enough to isolate the contamination at node 4.

4.1.3.2 Validation of the results for Scenario 3 of Net4

This subsection presents the validation of the results obtained for the third scenario of Net4, as previously done.

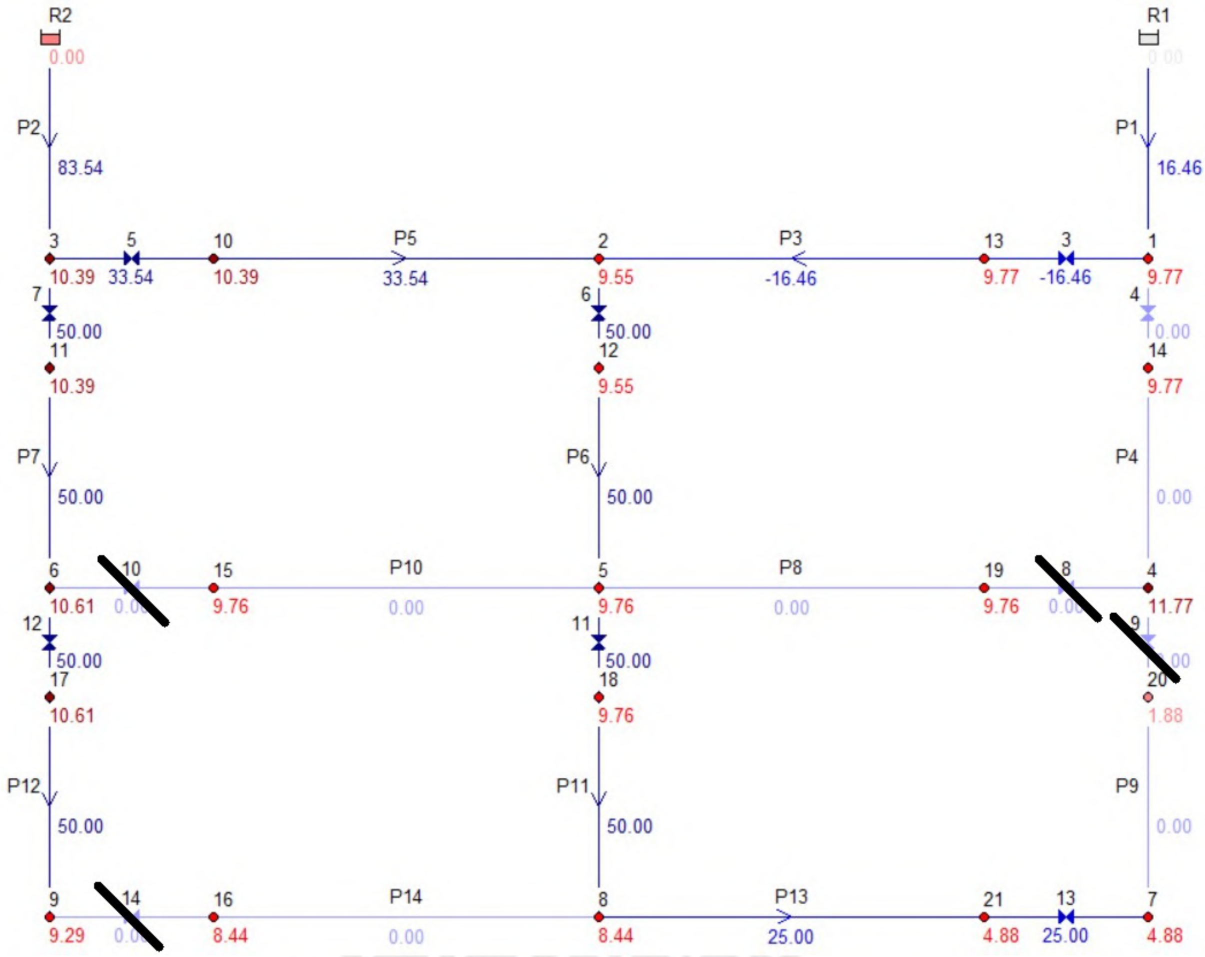

Figure 4.5: Validation of the results for Scenario 3 of Net4

Figure 4.5 demonstrates that the only alteration from Figure 4.4 is the pressure at node 4 ($p_4 = 12.03$), indicating that v_4 is open and v_5 is closed. The presence of pressure at node 4 means that any contamination flow would need to overcome this pressure to enter the system, resulting in a safer system compared to the previous scenario. At the end, the contamination was isolated as expected, proving that the model works properly.

4.1.4 Scenario 4

For this scenario, several of the parameters from our first case are changed. First, the points and demand levels are changed. In addition, the contamination entry points are changed to two and all valves are allowed to shut. Further details can be found in Table

	Demand (LPS)
N1	0
N2	25
N3	0
N4	25
N5	0
N6	0
N7	25
N8	0
N9	25

Table 4.9: Demands in Scenario 4 of Net4

To obtain the initial values of water flow in the pipes and pressures at the nodes the simulation in EPANET must be run with these new changes in the demands values. The new values are displayed in Figure 4.6.

For this scenario, the contamination sensor value was read at two nodes: N8 and N9 ($x_8 = 1$ and $x_9 = 1$). Also here, the level of contamination may be relevant to the model. If only one node can be isolated, the node with higher contamination may be the one isolated. This also depends on the water flow, as shown in objective function (3.6a).

Note that in this scenario, there is contamination at a node where there is also demand: $d_9 = 25$ and $x_9 = 1$.

Then, having modified all the initial values, run the simulation and collect the results, these will be presented in the following subsection.

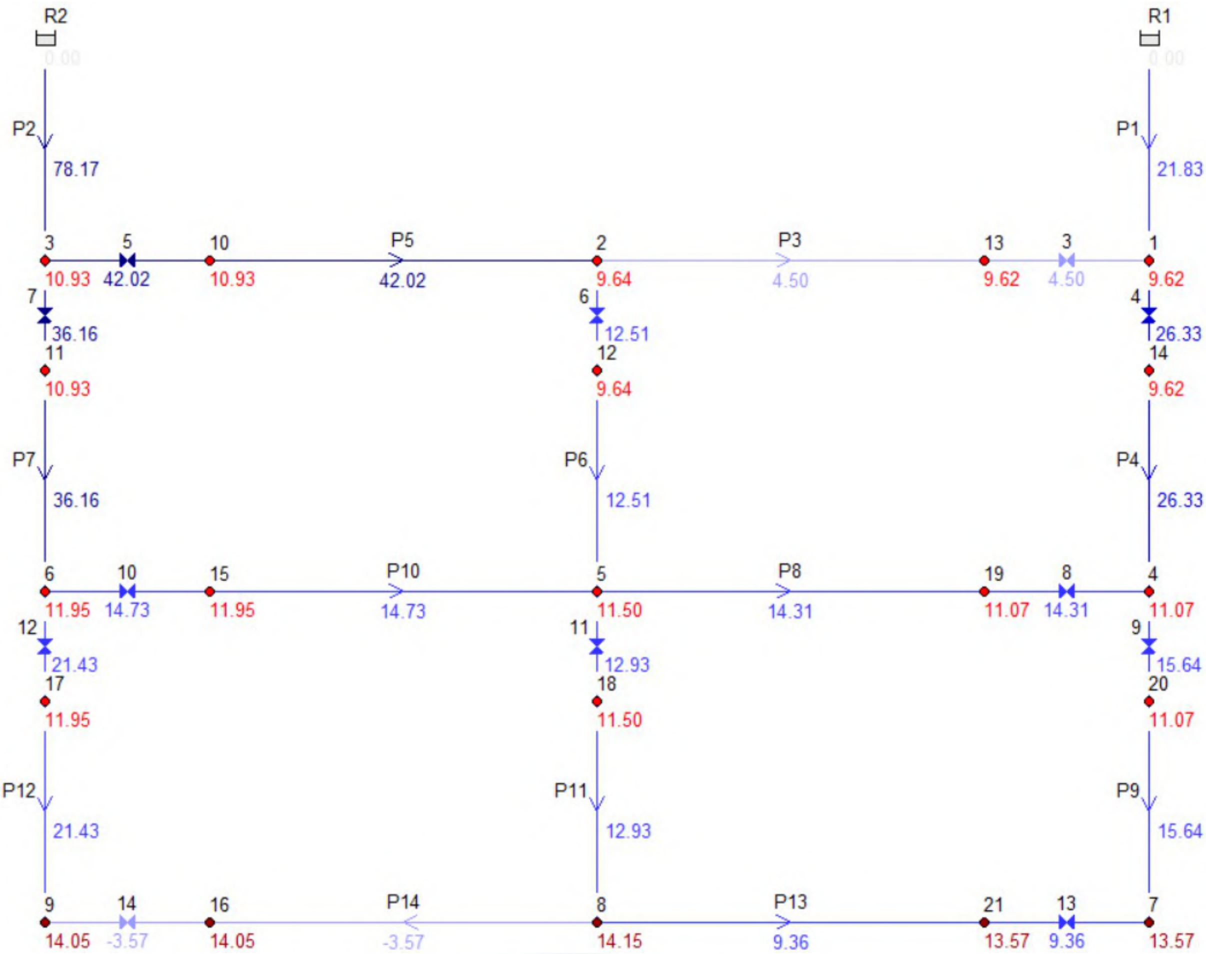

Figure 4.6: Initial values for Scenario 4 of Net4.

4.1.4.1 Results for Scenario 4 of Net4

For this scenario, the results are different from those of the previous ones because it is a random scenario with many different parameter. Table 4.10 shows the new valve arrangements in detail.

After inputting the initial values as shown previously, the solver took 47.308 seconds to find a solution. The objective function value is $8.439e^{-9}$.

v_3	v_4	v_5	v_6	v_7	v_8	v_9	v_{10}	v_{11}	v_{12}	v_{13}	v_{14}
0	1	1	1	1	1	1	1	0	1	0	0

Table 4.10: New valve values for Net4 Scenario 4

It is evident that all valves neighbouring node 8 are closed $(v_{11}, v_{13, v_{14}=0})$, with one of them also connected to node 9. However, as there is demand at node 9, v_12 is kept open, resulting in incoming water flow at node 9. Note that v_3 was closed, which is irrelevant for minimising contamination in this scenario.

It seems that the objective has been achieved with this result, which will be validated and analysed in the following subsection.

4.1.4.2 Validation of the results for Scenario 4 of Net4

This subsection presents the validation of the results obtained for the fourth scenario of Net4.

Figure 4.7 demonstrates that our MINLP model (3.6) effectively prevents pollution from spreading within the system and fulfill all the water demands $(q_{11}, q_{13}, q_{14} = 0,\ q_{12} = 25)$. However, it does not prevent pollution from leaving through a node with demand.

These were all the scenarios that were tested in this case study, and now case study 2 will be explained.

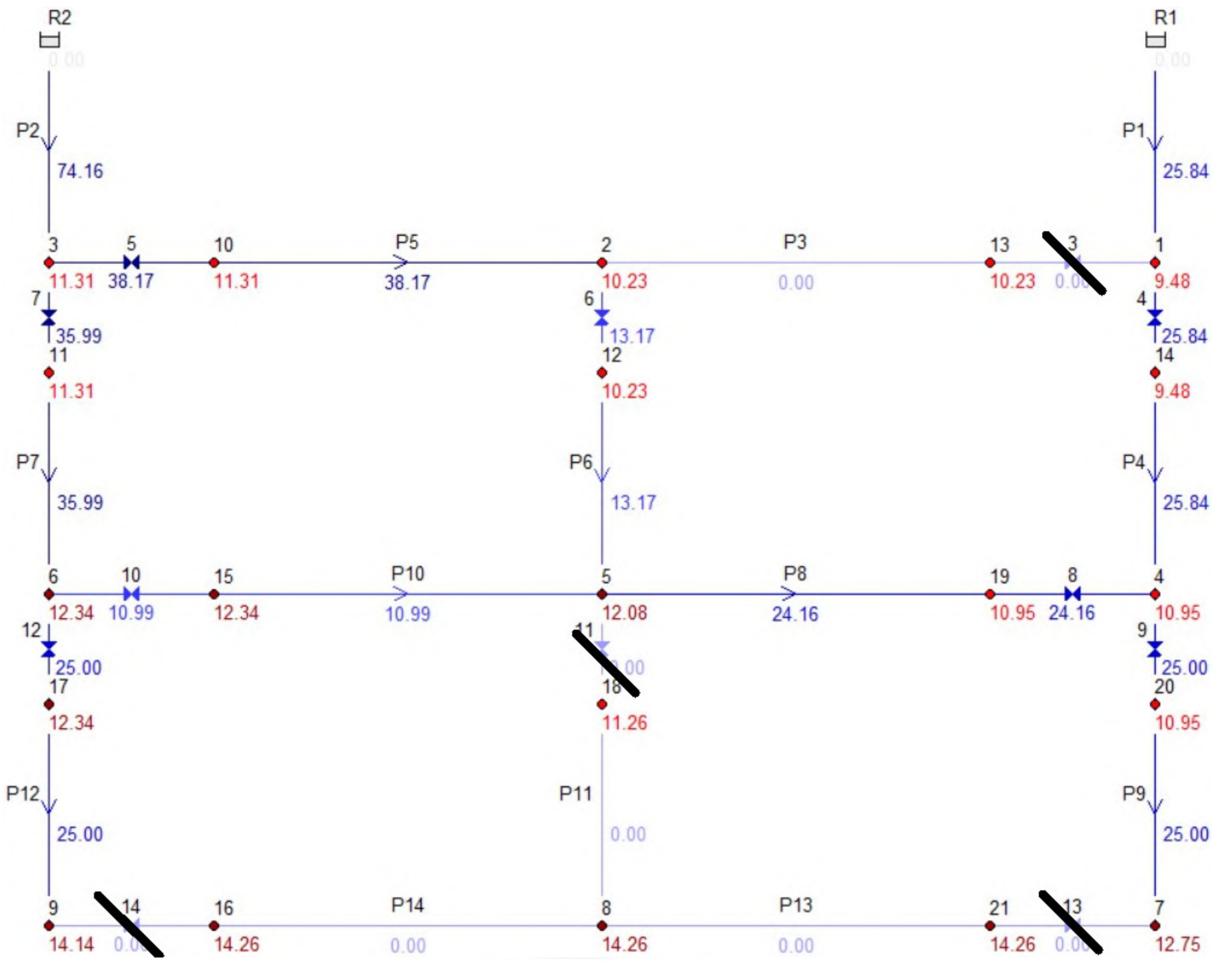

Figure 4.7: Validation of the results for Scenario 3 of Net4

	Elevation (m)
N1	1.8
N2	0.8
N3	1.8
N4	0.8
N5	1.8
N6	0.8
N7	1.8
N8	0.8

Table 4.11: Elevations of Case Study 2 nodes

4.2 Case Study 2: Test bench

This section offers a detailed explanation of the second case study, which is a simulation of the laboratory's implemented test bench. The system consists one reservoirs and one pump, R1 and P1 respectively, eight nodes (N1, N2, ..., N8), eleven pipes (L1, L2, ..., L11) and 10 valves $(v_1, v_2, ..., v_{10})$. This can be seen in Figure 4.8

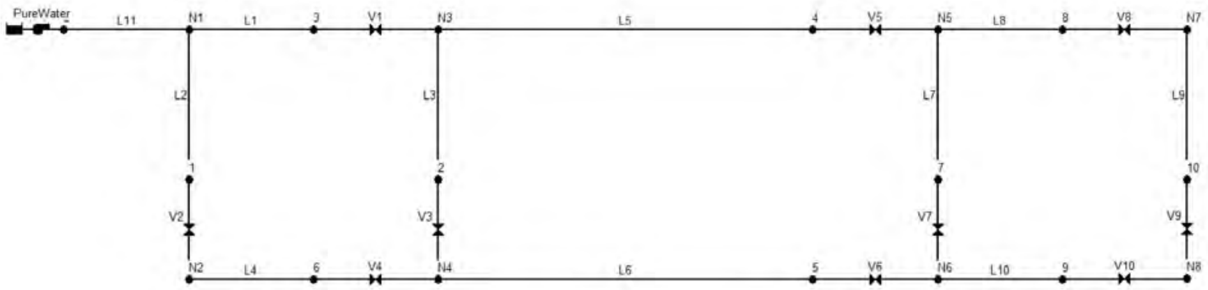

Figure 4.8: Case Study 2: Test bench in EPANET

As with the previous case, Tables 4.11 and 4.12 will display the elevations of the nodes and the physical characteristics of the pipes. It should be noted that there are additional pipe bends in the physical system whose equivalence in metres is unknown, but the distance has been slightly increased to compensate for this.

To conclude the explanation of the system, it is necessary to determine the direction of the positive water flow. Table 4.13 presents this information. In summary, the flow is positive from

	Diameter (mm)	Length (m)	Roughness Coeff. C
L1	20	2.5	100
L2	20	1	130
L3	20	1	130
L4	20	2.5	130
L5	20	25	130
L6	20	25	130
L7	20	1	130
L8	20	1	130
L9	20	1	130
L10	20	1	130
L11	20	1	130

Table 4.12: Characteristics of Case Study 2 Pipes

left to right and from top to bottom.

	Positive flow direction
L1	N1 $\longrightarrow$ N3
L2	N1 $\longrightarrow$ N2
L3	N3 $\longrightarrow$ N4
L4	N2 $\longrightarrow$ N4
L5	N3 $\longrightarrow$ N5
L6	N4 $\longrightarrow$ N6
L7	N5 $\longrightarrow$ N6
L8	N5 $\longrightarrow$ N7
L9	N7 $\longrightarrow$ N8
L10	N6 $\longrightarrow$ N8
L11	R1 $\longrightarrow$ N1

Table 4.13: Case Study 2: Positive flow direction

In the following subsection, the testing scenarios will be explained and the results will be presented.

4.2.1 Scenario 1

In this scenario, the system has all its valves available for modification, but there is only demand in one node. The demand for this is fixed and constant over time, and it is not affected by pressure. More details are provided in Table 4.14.

	Demand (LPM)
N1, ... , N7	0
N8	2

Table 4.14: Demands in Scenario 1 of Case study 2

To start the test, it is essential to provide the MINLP problem with the initial values of the system when the contamination sensor indicates a risk level. Therefore, the simulation is run with these initial parameters to obtain the initial water flows (Q_0) and pressures (P_0). The initial valve positions (V_0) are already known and must be provided to the algorithm. The valves' initial positions are not all set to 1 (open). Table 4.15 displays the initial position of the system's valves for this first scenario.

v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	v_9	v_{10}
1	0	0	0	1	0	1	1	1	1

Table 4.15: Initial position of valves in scenario 1 of Case Study 2

Figure 4.9 shows the simulation results, displaying the initial flows and directions in a blue colour scale, as well as the initial pressure in the nodes in a red colour scale.

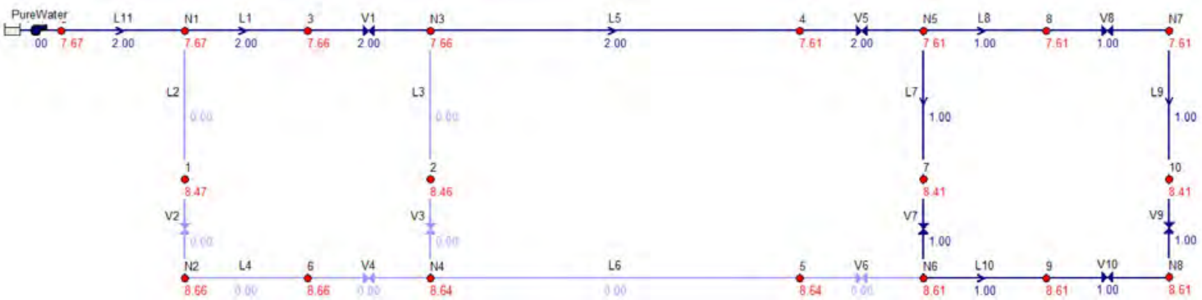

Figure 4.9: Initial values for Scenario 1 of Case Study 2.

To run the solver with the model (3.6), it is necessary to create the matrices A, A_{out}, V_p and M, in this case $A \in R^{22x9}$, $A_{out} \in R^{9x22}$, $V_p \in R^{22}$ and $M \in R^{22}$. Since there is no valve in pipe L11, $V_{p_{11}} = V_{p_{22}}$ = 0, the rest is equal to 1.

For this scenario, the contamination sensor value was read at node 7 ($x_7 = 2$). However, the value of contamination is not relevant.

4.2.1.1 Results for Scenario 1 of Case Study 2

This subsection presents and analyses the results obtained for Scenario 1 of Case Study 2 using the MINLP method (3.6) described in the previous section.

After inputting the initial values as shown previously, the solver took 22.577 seconds to find a solution. The objective function value is $4.99346e^{-8}$, and the Table 4.16 displays the new valve positions.

v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	v_9	v_{10}
1	1	1	1	0	1	1	1	0	1

Table 4.16: New valve values for Case Study 2 Scenario 1

Due to the extremely low value of the objective function, it can be assumed that it is equal to 0. Therefore, it can be interpreted that there is no polluted flow exiting the system through any of the pipes connected to node 7. Valve 8 (v_8) has not been closed and is located in a pipe adjacent to the contamination node, therefore it should be cleaned. Later, when explaining the logic for cleaning the pipes, this will be a problem, for solving this, an additional constraint (3.7) was added to prioritize the closure of adjacent pipes.

4.2.1.2 Validation of the results for Scenario 1 of Case Study 2

This subsection presents the validation of the previously obtained results for this scenario of Case Study 2. The validation will be performed through simulation in EPANET. The valve values will be changed, and the new system values will be analyzed.

Figure 4.10 illustrates that there is no water flow in the pipes connected to the contaminated node, due to the closed valves v_5 and v_9, and in order to satisfy the demand the valves

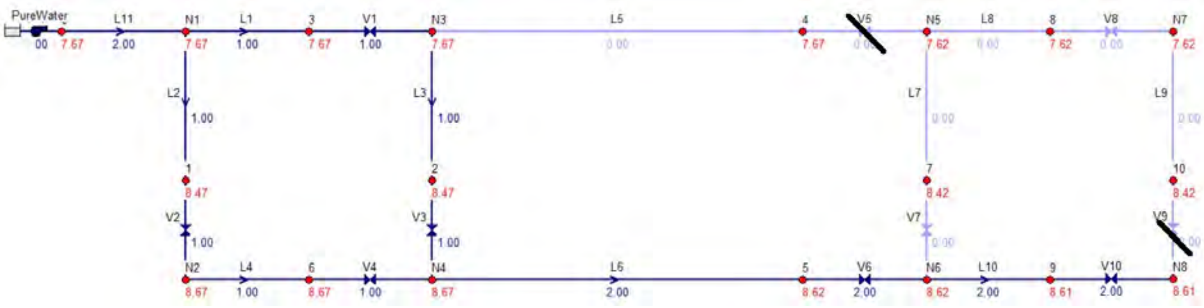

Figure 4.10: Validation of the results for Scenario 1 of Net4

v_2, v_3, v_4, v_6 were opened.

Thanks to this simulation, it can be stated that the model (3.6) achieves its intended purpose, isolate the contamination.

4.2.2 Scenario 1.2

This sub-section requires the use of the mode with the additional constraint (3.7) to close the valves directly connected to the contaminated node. This scenario will be referred to as Scenario 1.2.

4.2.2.1 Results for Scenario 1.2

After inputting the initial values as shown previously, the solver took 13.180 seconds to find a solution. The objective function value is $-1.91931e^{-10}$, and the Table 4.17 displays the new valve positions.

v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	v_9	v_{10}
1	1	1	1	1	1	1	0	0	1

Table 4.17: New valve values for Case Study 2 Scenario 1.2

It is evident that the objective has been achieved and the solution has been found in less time due to the additional constraint resulting in only one solution (assuming valves are present in all pipes).

Now, validation will occur.

4.2.2.2 Validation of the results for Scenario 1.2 of Case Study 2

After changing the valve position, the simulation shown in Figure 4.11 was obtained.

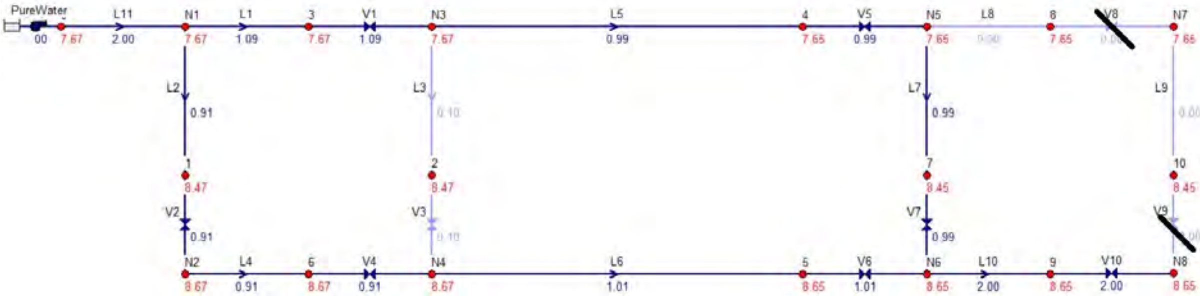

Figure 4.11: Validation of the results for Scenario 1 of Net4

Thanks to this simulation, it can be stated that the model (3.6) achieves its intended purpose, isolate the contamination and also picked to close the valves in the adjacent pipes of the contaminated node.

4.2.3 Scenario 1.3

Assuming no valve is available in pipe L8, i.e. $_{V}p_8 = 0$, for scenario 1.3.

4.2.3.1 Results for Scenario 1.3

After inputting the initial values as shown previously, the solver took 18.259 seconds to find a solution. The objective function value is $-1.8e^{-10}$, and the Table 4.18 displays the new valve positions.

In this case, although the results differ from the previous ones, it is still important to meet the demand and isolate the contamination. The following section will validate this.

v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	v_9	v_{10}
1	1	1	0	1	1	0	1	0	1

Table 4.18: New valve values for Case Study 2 Scenario 1.3

4.2.3.2 Validation of the results for Scenario 1.3 of Case Study 2

After changing the valve position, the simulation shown in Figure 4.12 was obtained.

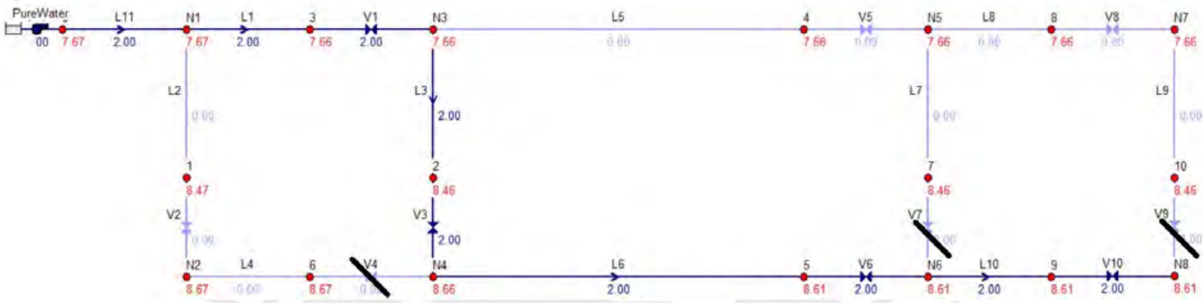

Figure 4.12: Validation of the results for Scenario 1 of Net4

Thanks to this simulation, it can be stated that the model (3.6) achieves its intended purpose, isolate the contamination and also picked to close the valves in the adjacent pipes of the contaminated node.

4.2.4 Scenario 2

In this scenario, the system has all its valves available for modification, there is only demand in three nodes (N5, N6 and N8). The demand for this is fixed and constant over time, and it is not affected by pressure. More details are provided in Table 4.19.

To start the test, it is essential to provide the MINLP problem with the initial values of the system when the contamination sensor indicates a risk level. Therefore, the simulation is run with these initial parameters to obtain the initial water flows (Q_0) and pressures (P_0). The initial valve positions (V_0) are already known and must be provided to the algorithm. The valves' initial positions are not all set to 1 (open). Table 4.20 displays the initial position of the

	Demand (LPM)
N1, ... , N4	0
N5	1
N6	1
N7	0
N8	1

Table 4.19: Demands in Scenario 2 of Case study 2

system's valves for this first scenario.

v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	v_9	v_{10}
1	1	1	1	0	1	0	1	1	1

Table 4.20: Initial position of valves in scenario 2 of Case Study 2

Figure 4.13 shows the simulation results, displaying the initial flows and directions in a blue colour scale, as well as the initial pressure in the nodes in a red colour scale.

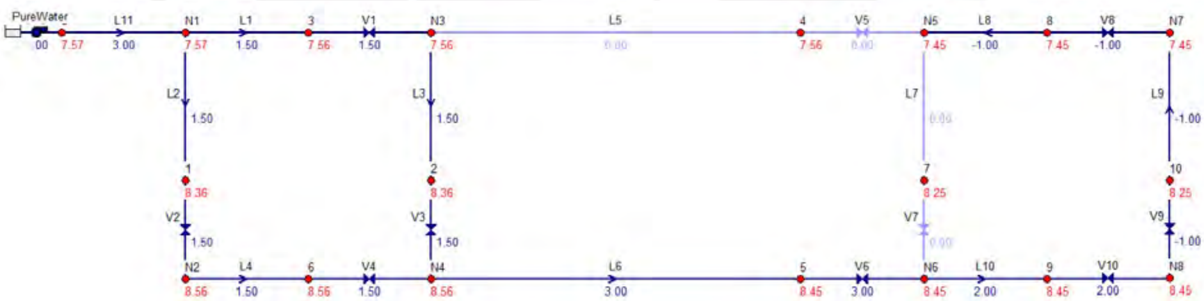

Figure 4.13: Initial values for Scenario 2 of Case Study 2.

For this scenario, the contamination sensor value was read at node 7 ($x_7 = 2$). However, the value of contamination is not relevant.

It is important to note that this system has a unique characteristic: the water flow only follows one path, and in two pipes, there is a negative flow.

4.2.4.1 Results for Scenario 2 of Case Study 2

This subsection presents and analyses the results obtained for Scenario 2 of Case Study 2 using the MINLP method (3.6) described in the previous section.

After inputting the initial values as shown previously, the solver took 46.978 seconds to find a solution. The objective function value is $2.12311e^{-8}$, and the Table 4.21 displays the new valve positions.

v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	v_9	v_{10}
1	1	1	1	1	1	1	0	0	1

Table 4.21: New valve values for Case Study 2 Scenario 2

Due to the extremely low value of the objective function, it can be assumed that it is equal to 0. Therefore, it can be interpreted that there is no polluted flow exiting the system through any of the pipes connected to node 7.

Note that with the first algorithm, the adjacent pipes have already been selected to be closed. The next step is the validation.

4.2.4.2 Validation of the results for Scenario 2 of Case Study 2

This subsection presents the validation of the previously obtained results for this scenario of Case Study 2. The validation will be performed through simulation in EPANET. The valve values will be changed, and the new system values will be analyzed.

Figure 4.14 illustrates that there is no water flow in the pipes connected to the contaminated node, due to the closed valves v_8 and v_9, and in order to satisfy the demand the valves v_5, v_7 were opened.

Thanks to this simulation, it can be stated that the model (3.6) achieves its intended purpose, isolate the contamination and also close the adjacent valves that will be important for cleaning logic.

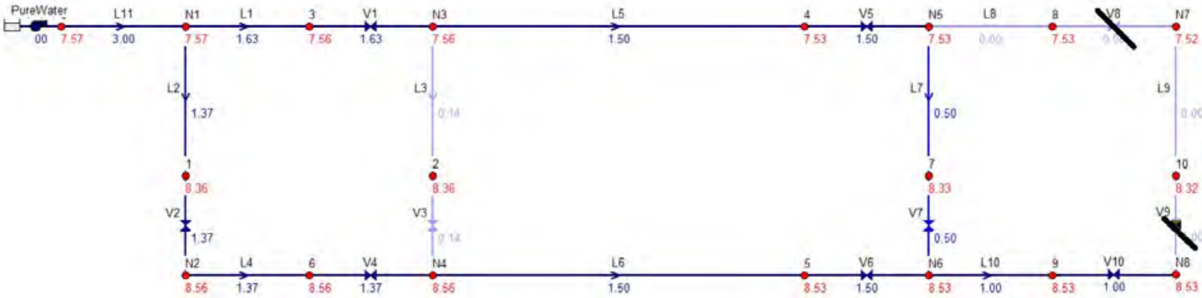

Figure 4.14: Validation of the results for Scenario 3 of Case Study 2

4.2.5 Scenario 3

In this third scenario, the system has all its valves available for modification, there is only demand in three nodes (N5, N6 and N8) like in Scenario 2. The demand for this is fixed and constant over time, and it is not affected by pressure. More details are provided in Table 4.19.

To start the test, it is essential to provide the MINLP problem with the initial values of the system when the contamination sensor indicates a risk level. Therefore, the simulation is run with these initial parameters to obtain the initial water flows (Q_0) and pressures (P_0). The initial valve positions (V_0) are already known and must be provided to the algorithm. The valves' initial positions all set to 1 (open) in this case.

Figure 4.15 shows the simulation results, displaying the initial flows and directions in a blue colour scale, as well as the initial pressure in the nodes in a red colour scale.

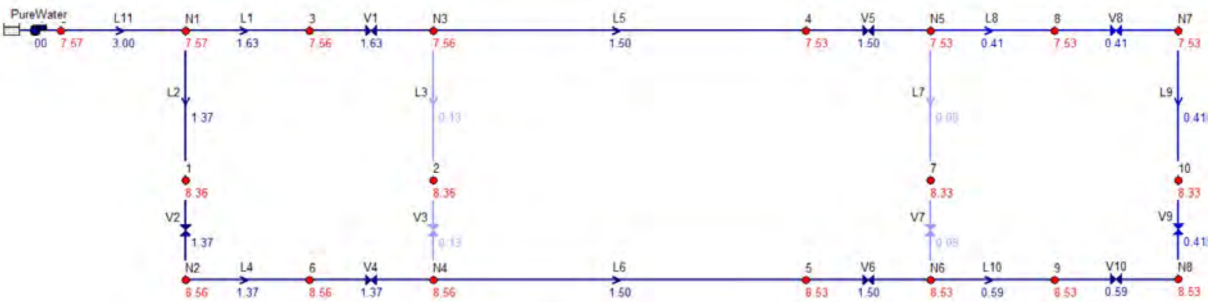

Figure 4.15: Initial values for Scenario 3 of Case Study 2.

For this scenario, the contamination sensor value was read at node 3 ($x_3 = 2$). However, the value of contamination is not relevant.

4.2.5.1 Results for Scenario 2 of Case Study 2

This subsection presents and analyses the results obtained for Scenario 2 of Case Study 2 using the MINLP method (3.6) described in the previous section.

After inputting the initial values as shown previously, the solver took 26.933 seconds to find a solution. The objective function value is $2.35035e^{-10}$, and the Table 4.22 displays the new valve positions.

v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	v_9	v_{10}
0	1	0	1	0	1	0	1	1	1

Table 4.22: New valve values for Case Study 2 Scenario 3

It is worth noting that, on this occasion, the valves directly connected to node 3 (the contaminated node) have been closed to isolate the contamination. v_7 was also closed, although this was unnecessary and did not affect the final objective.

4.2.5.2 Validation of the results for Scenario 3 of Case Study 2

This subsection presents the validation of the previously obtained results for this scenario of Case Study 2. The validation will be performed through simulation in EPANET. The valve values will be changed, and the new system values will be analyzed.

Figure 4.16 illustrates that there is no water flow in the pipes connected to the contaminated node, due to the closed valves v_1, v_3 and v_5.

Thanks to this simulation, it can be stated that the model (3.6) achieves its intended purpose, isolate the contamination and also close the adjacent valves that will be important for cleaning logic.

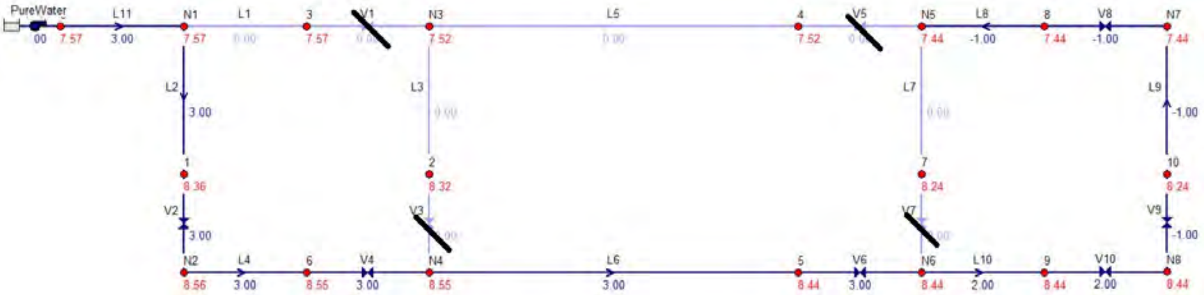

Figure 4.16: Validation of the results for Scenario 3 of Case Study 2

This chapter concludes the simulation tests of the model developed in this thesis. In the next chapter, we will explain the updates that the laboratory test bench has undergone before proceeding to the tests.

Chapter V

Update of the test bench

This chapter presents the updates made to the test bench to enable full automation of the tests. The modifications to the test bench will be detailed here. For a detailed construction of the test bench, please refer to the thesis [12].

In Figure 5.1, the SCADA system in the Freelance Operations software is displayed, showing pipes, valves, pumps, sensors, and tanks. They already have their name tags.

Valves ZV1 and ZV2 enable the filling of water tanks B1 and B2. Tank B1 contains clean water, while tank B2 contains contaminated water, specifically water with salt, which will help us to ensure that the conductivity sensors QI1, QI2, QI3, and QI4 provide a value that we can interpret as contamination. Valves SV1, SV2, and SV3 are solenoid valves that allow contaminated water from tank B2 to enter the system. Valves V1 to V10 will be used to minimise contamination in our system. Some of these valves are solenoid valves that allow water to pass in one direction only (V1, V2, V4, V6), while the others are motorised ball valves that take approximately 7 seconds to complete their opening or closing. Additionally, we have AV1 and AV2 valves. AV8 comprises analogue valves that enable the simulation of controlled demand in various nodes of the system and the removal of contaminated water through an exhaust. The system also includes pressure sensors (PI1 to PI5), conductivity sensors (QI1 to QI4), and flow

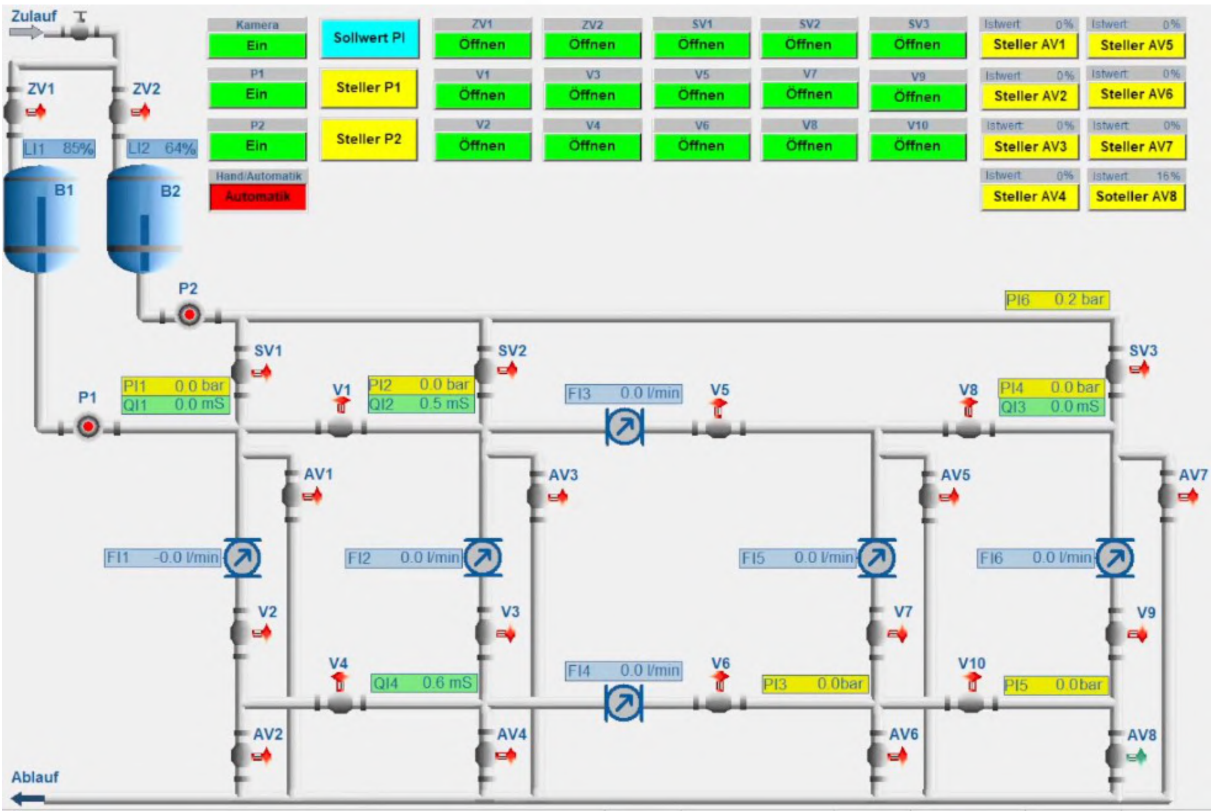

Figure 5.1: Test bench SCADA

sensors (FI1 to FI6).

5.1 Valve updates

This section explains the changes that have been made to some of the valves, starting with the replacement of all manual valves.

The three valves that allowed contaminated water to enter our system have been replaced with solenoid valves, these are SV1, SV2 and SV3. They are of the same type as valves V1, V2, V4 and V6, they only allow flow in one direction. One of these valves is shown in Figure 5.2.

Figure 5.2: New ZV1 Valve

The other valves that were modified were those that were required to allow water to leave the system and 8 valves were installed, one at each node. These valves are analogue and operate in a range from 0 to 100% open. Figure 5.3 shows one of these valves, in this case AV3.

These valves operate on 24 volts and are unfortunately quite slow, as you will see when analysing the tests. They also have a mechanism for manual opening and closing.

Figure 5.3: Valve for demand AV3

These were the changes made with respect to the valves, now the changes to the sensors will be explained.

5.2 Sensor updates

This section discusses the changes made to the system's sensors.

The pressure sensors PI1,...,PI5 remained unchanged, while the conductivity sensors were replaced with a new model from Greisinger, as shown in figure 5.4. Technical details about the new sensors can be found in the appendices. The new sensors, QI1, QI2, QI3, and QI4, are located at nodes N1, N3, N7, and N3, respectively.

In addition to the sensor changes mentioned above, new flow sensors were added to the system, these are FI1, FI2, FI3, FI4, FI5 and FI6 located in pipes L2, L3, L5, L6, L7 and L9 respectively. These are sufficient and necessary to be able to know when flow exists and in which direction they flow through the system, to calculate the flows in the pipes where there is no sensor it is enough to apply the equation of mass conservation (3.1) in the corresponding nodes. Figure 5.5 displays the FI2 sensor situated in the L3 pipe.

Figure 5.4: Conductivity Sensor QI2

This flow sensor is capable of detecting reverse flow when it occurs in the opposite direction to the pre-set flow direction. In this case, a negative flow will be applied.

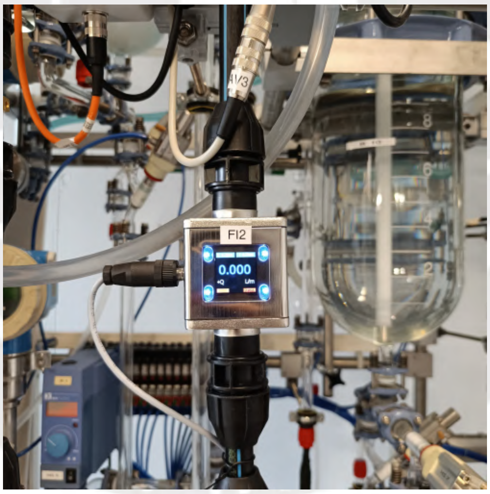

Figure 5.5: Flow sensor FI2

These are all the updates that were made to the hardware of the system. Figure 5.5 shows the entire updated system, while 5.6 provides a closer look at nodes N1 and N2, as well as their respective sensors, valves, and pipes.

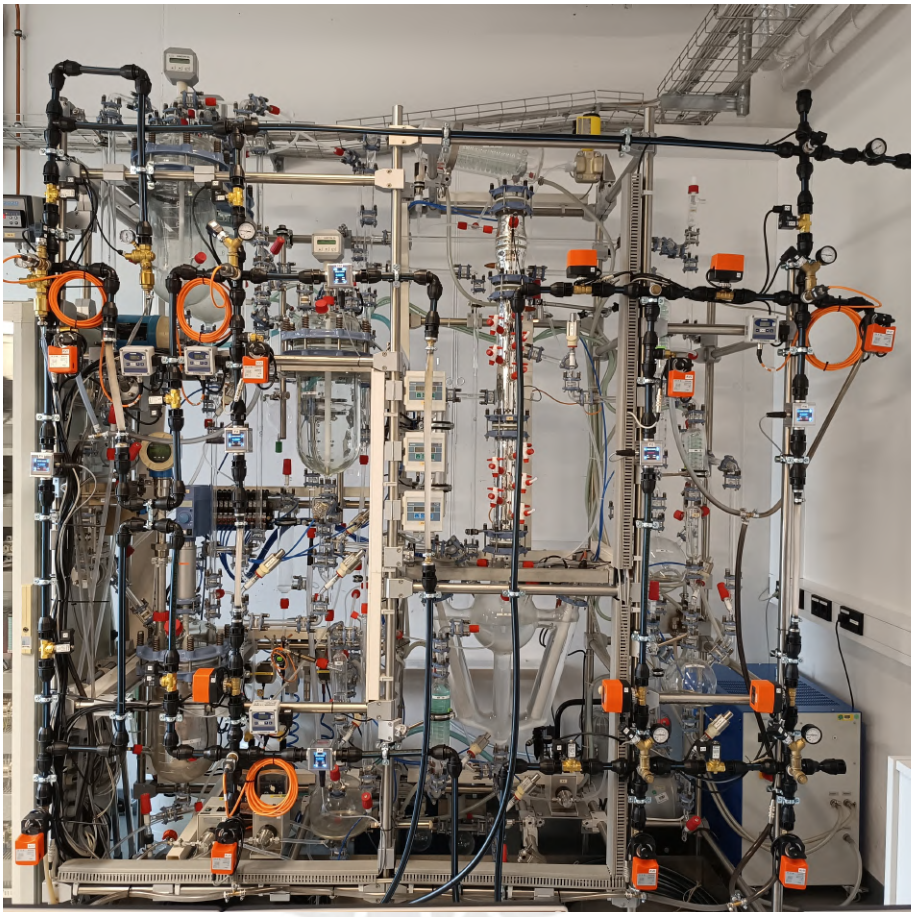

Figure 5.6: Updated Test Bench

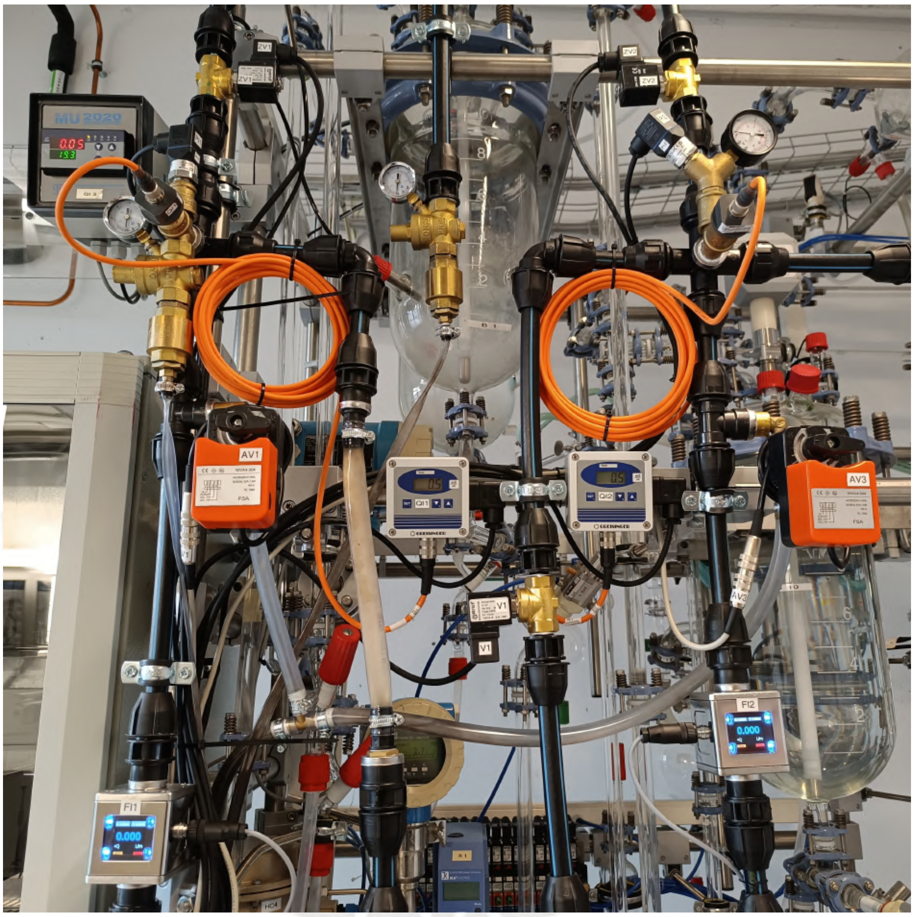

Figure 5.7: Close look to N1 and N2

5.3 Software Updates

This section briefly explains some important changes to the software that controls the system without going into too much detail.

As shown in Figure 5.1, the SCADA system has undergone changes, including the addition of new valves and sensors. It is worth noting the inclusion of a new button that enables the automatic use of the analogue valves AV1, AV2, AV3, ..., AV8.

During the initial tests, it was noticed that the analog value for these valves was not changing when it came from the OPC server. This was due to the blocks of these valves in the Freelance Engineering program being set to manual mode, which was a significant problem. The solution proposed and implemented was to add a new binary variable (in this case the "automatic/manual" button) that will change the working mode of all the valves blocks, allowing them to be modified manually in the SCADA model while this block in in manual mode, and allowing only the OPC value to be set when the button is in Automatic mode. Figure 5.8 displays the new variable linked to the block that manages the opening and closing of valves AV1 and AV2, which are enclosed in a red rectangle.

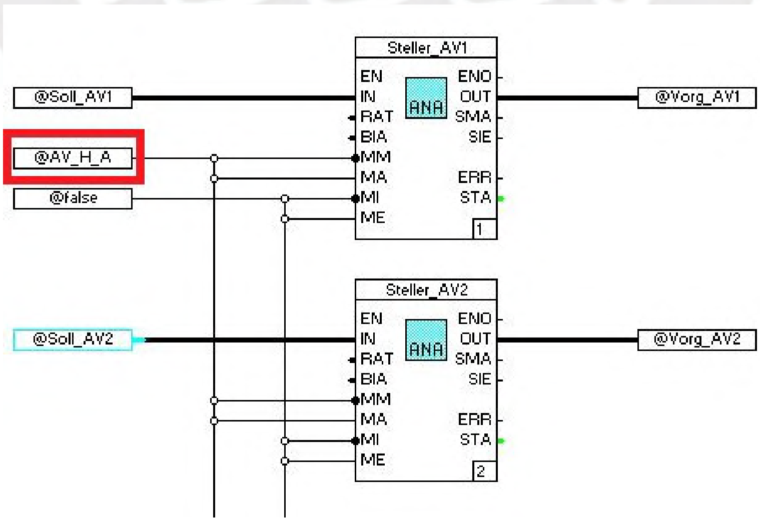

Figure 5.8: Analogic Valves control Blocks

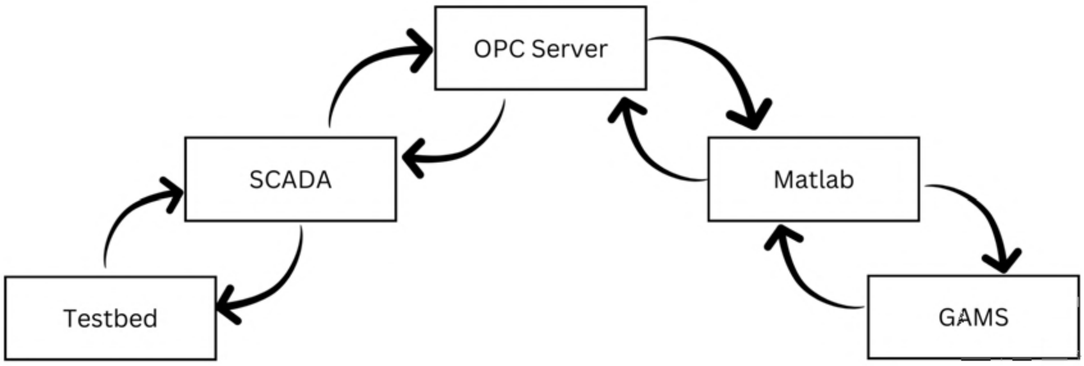

Figure 5.9: Control system information flow

The communication between the testbed and GAMS occurs through Matlab. To achieve this, we utilized the GAMS Matlab API package, which includes several sub-packages that facilitate the control of the GAMS system and the transfer of data between GAMS and Matlab.

Figure 5.9 illustrates the data flow from the test bed to GAMS, which is responsible for finding a solution. The solution is then returned to the test bed for implementation.

Chapter VI

Results from the test bench

This chapter presents the results of the optimization model implemented for this thesis on the laboratory test bed described in [12] and updated in the previous chapter. Only scenarios 1, 1.2, and 2 were tested.

6.1 Flushing of the pipes

It is important to mention that, for these tests, a period of flushing the pipes will be added to remove any possible contamination that may remain in the pipes near the affected node. The procedure involves opening the valves that were previously closed one by one.

The valves of the pipes connecting to an upstream node, i.e. the pipes that have an inflow to the contaminated node, should be opened first. Then, the valves of the downstream nodes should be opened one by one. This logic was decided upon because contamination is assumed to spread more towards the direction of flow, i.e. in the direction of the downstream nodes. Flushing these pipes at the end ensures that they are thoroughly cleaned. To obtain information about the pipes, refer to the initial data and the direction of the flows. If sensors are not present in all pipes, the flow conservation equation (3.1) can be used to calculate the necessary data.

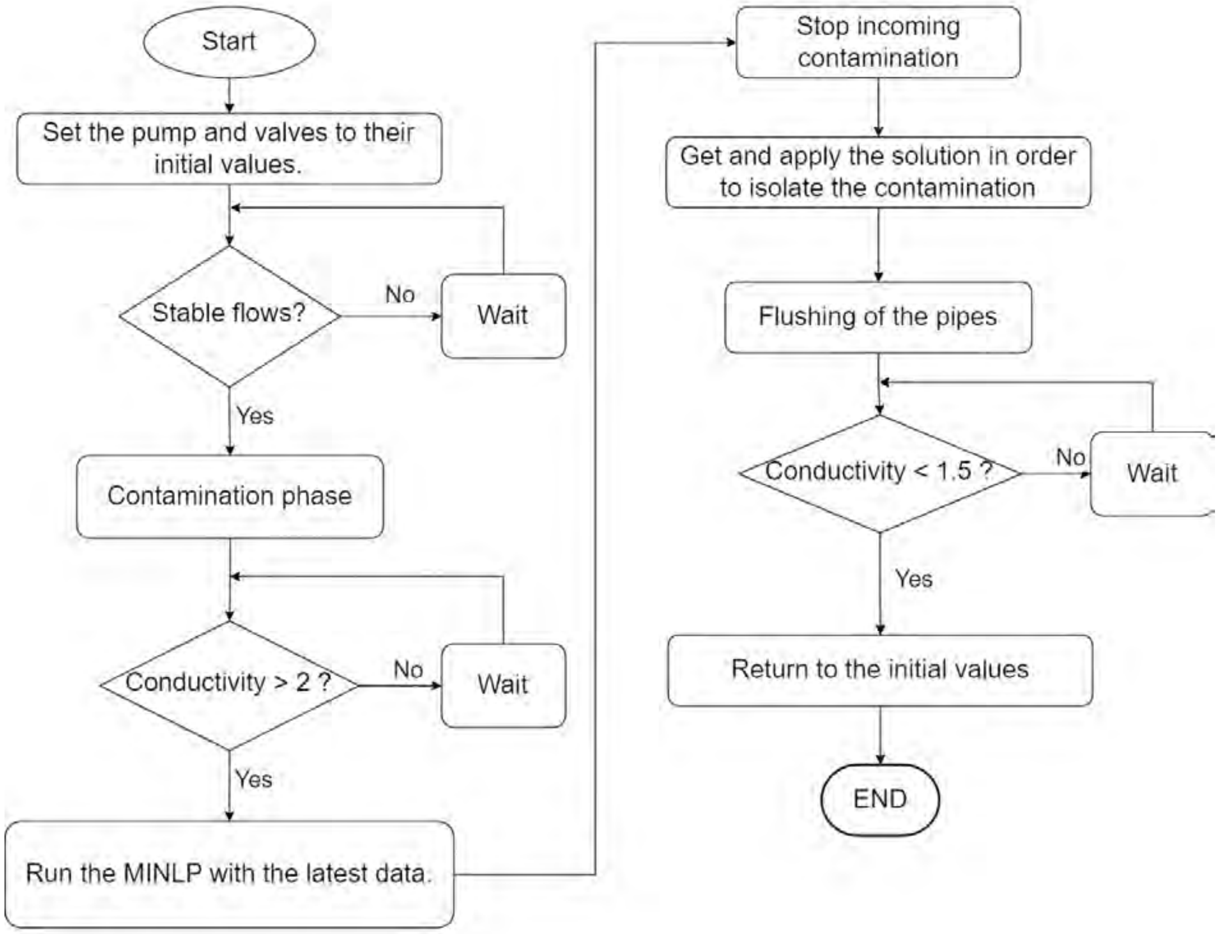

Figure 6.1: General Flowchart of the Tests

Figure 6.1 presents a general flow diagram of the entire test conducted for the aforementioned scenarios with the flushing stage included. All scenarios will adhere to this flowchart, and graphs of the complete process will be presented and explained for each case.

6.2 Scenario 1

This section analyses the results obtained in the test bench when applying the solution for scenario 1 of case study 2. Table 4.16 shows the valve configuration. To flush the pipes, V5 valve will open first, followed by V9 valve, in accordance with the logic of opening upstream valves first. Refer to Figure 6.2 for the specific flow diagram.

Following the test, a graph displaying a significant amount of data is obtained. Figures 6.3 and 6.4 will be analysed to highlight the most relevant points of these results. First, it can be observed that a stable state of the system can be achieved after approximately 27 seconds, particularly in terms of the flows. It can be seen that the contamination process begins approximately after 31 seconds, as P2 changes from 0 to 1, and it is implicit that SV3 also changes to 1 (open). At the second point, around 36 seconds in, it is evident that the contamination level measured by QI3 exceeds the value of 2. Therefore, the current values of flows (Q_0), pressures (P_0), and valves (V_0) become the initial values of our MINLP, which then begins searching for a solution.

It is evident that the pressure increases at all nodes during the contamination phase due to the flow of contamination. It is important to note that our model does not account for this additional flow, but instead treats pollution as a mass that mixes with the existing water flow. Unfortunately, the sensor FI6 provides an inaccurate flow reading in the at around $t = 35s$ due to the mixing of two flows. However, in $t = 55s$, a value of 1.7 is observed just after turning off P2 and closing SV3 but this value is almost the same as in $t = 46s$ (while contamination phase is going on), indicating an increase in flow due to incoming contamination.

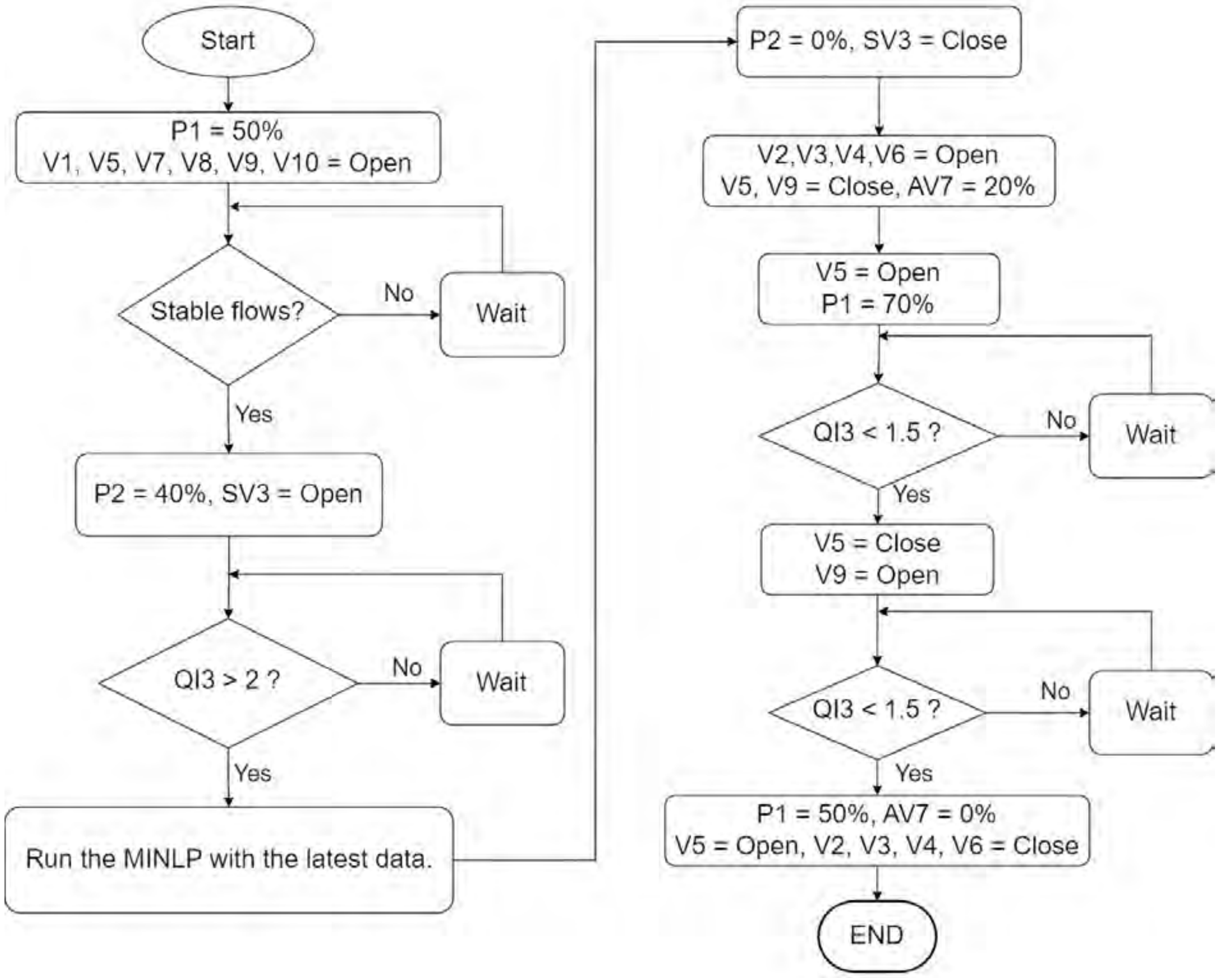

Figure 6.2: Flowchart Scenario 1

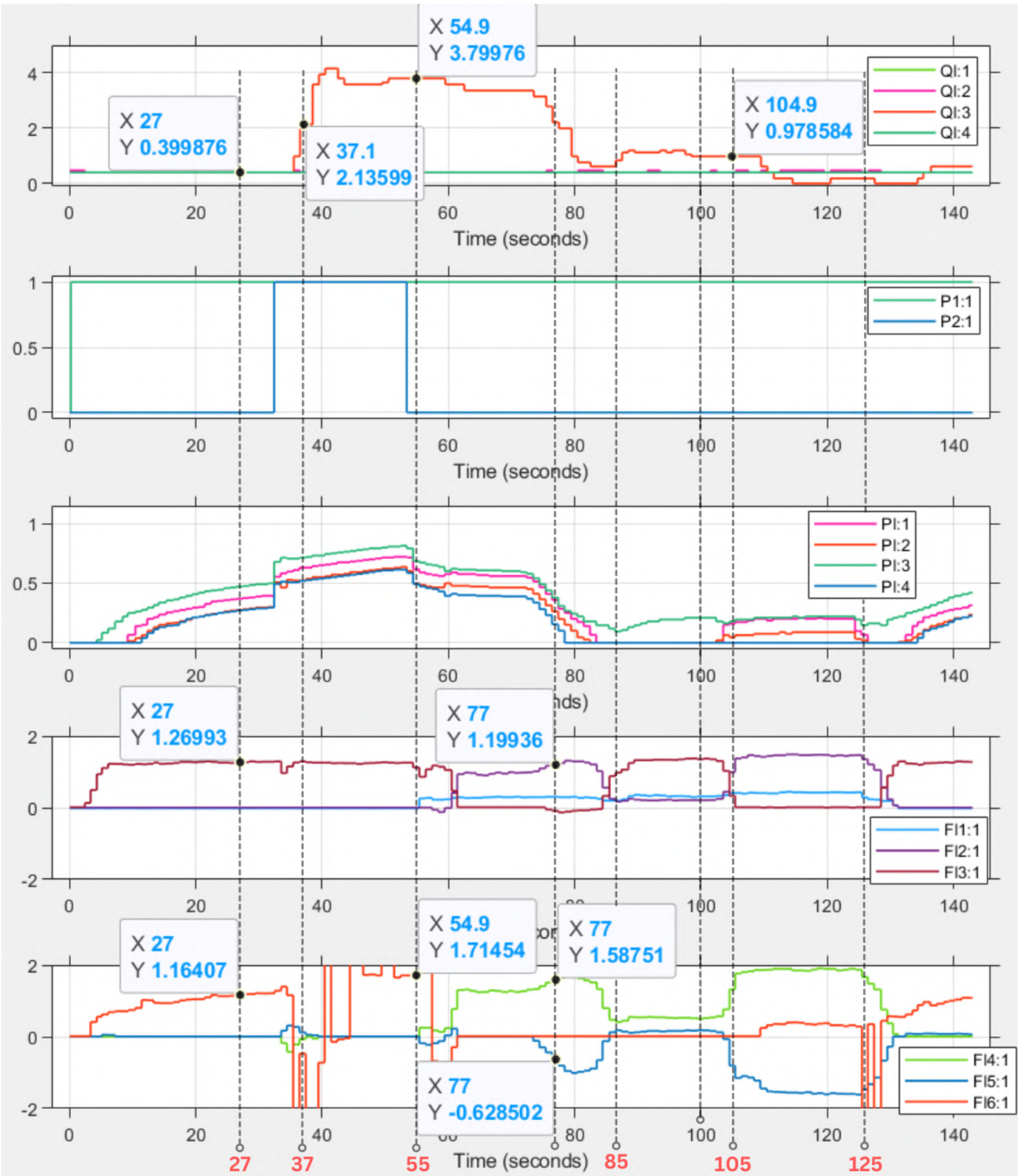

Figure 6.3: Scenario 1: Results 2

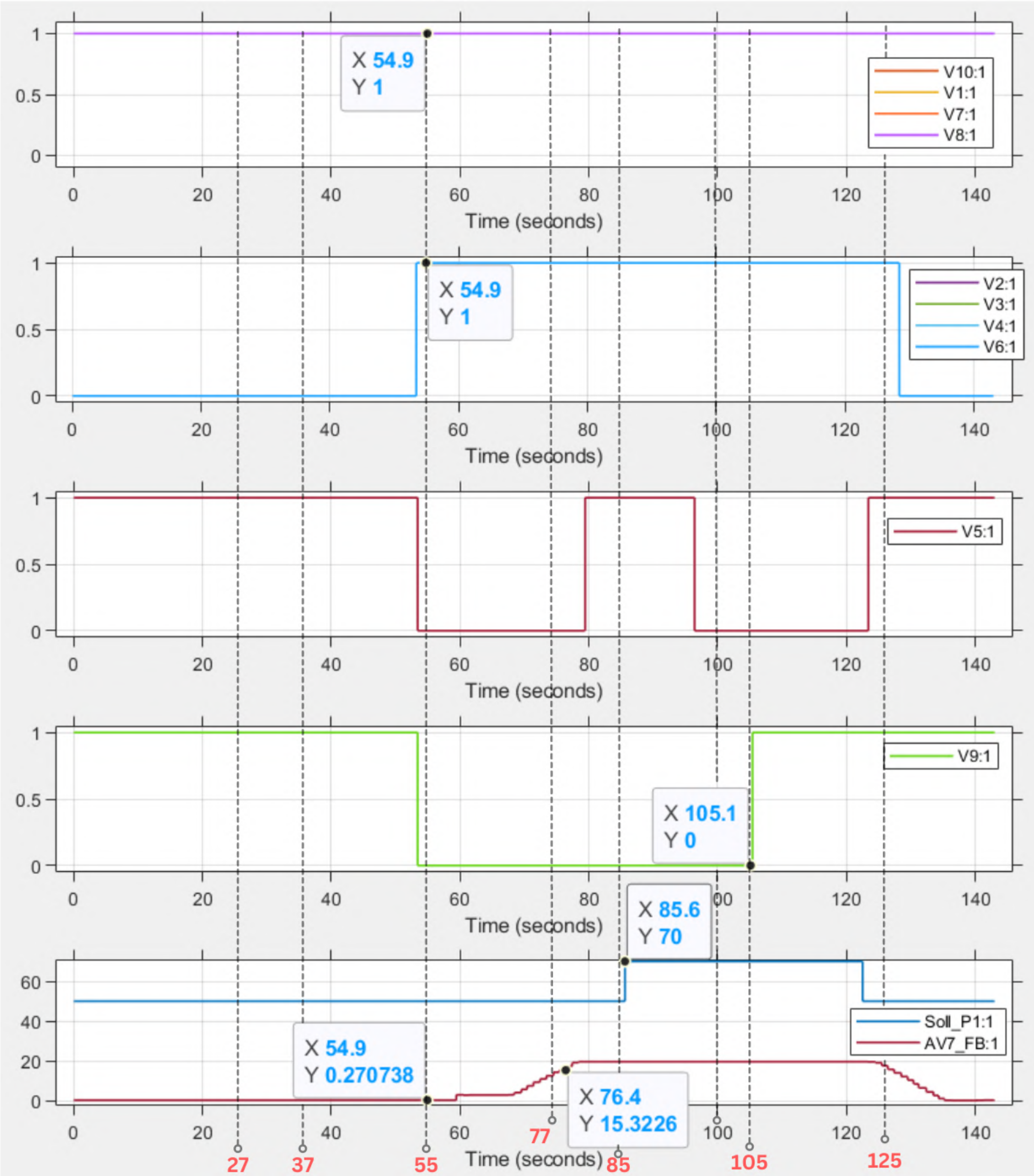

Figure 6.4: Scenario 1: Results 2

The pressure drop resulting from the cessation of incoming contamination flow is visible at $t = 55s$. Additionally, valves V5 and V9 close while V2, V3, V4, and V6 open, and V1, V7, V8, and V10 remain open. After a few seconds, the new flows stabilize and meet the expected values. The flow through pipe L9, known as the flow in FI6, is currently at 0. To calculate the flow in pipe 8, use the simple operation $q_8 = q_5 - q_7$. This results in $q_8 = 0$ until valve AV7 begins to open. This is the point where contaminated water will be drained. Valve AV7 takes almost 10 seconds to open up to 20%, and at approximately 17% $(t = 77s)$, a negative flow in q_7 (-0.6 at this exact point in FI5) can already be seen, which is equal to a 0.6 positive flow in q_8.

On the other side of the system, the flow at L5 (q_5) is zero because v_5 is zero. As a result, there is an increase in the readings at sensors FI1 and FI2, whose sum is equal to the flow measured at FI4 $(q_4 = q_1 + q_3)$. However, 0.3 of the flow is lost through q_{18}, which is the same as the flow of q_7 but in the opposite direction. Therefore, only 1.2 LPM reaches the initial demand point. This proves that the contamination in our test bench has been isolated and the demand is still being met.

At t=85 s, the graph reveals several significant observations, which are listed below:

1. The valve AV7 is already open at its desired point, resulting in negative flow in FI5 and the water starting to exit through AV7.

2. Although the order to open V5 for flushing has been given, it is not yet fully open, as evidenced by the FI3 flow remaining at 0.

3. The contamination level QI3 has decreased along with the system pressure. This is due to the opening of AV7, which allowed a significant amount of contaminated water to escape, resulting in a decrease in concentration.

To meet the required demand level, the system pressure needs to be increased. Therefore, the pump power will be increased to 70%, as indicated by the Soll_P1 signal around 85 seconds. At this point on the right, V5 takes about 7 seconds to close completely, meaning that it is in a waiting state before V9 can be opened. The flow of 1.4 read for FI3 confirms that the L5 pipe has been cleaned. It can be seen that there is a slight increase in contamination in QI3 when pipes 5 and 8 are flushed, as the dirty waste water returns to the node with increased pressure. However, the level of contamination decreases as the waste water leaves the system.

$T = 105s$ and $t = 125s$ are the start and end of pipe 9 cleaning time. However, the flow sensor FI6 indicates that the flushing is in the wrong direction, as it shows a positive flow from N7 to N8 4.13. The desired flow direction is the opposite, as the contamination is in N7 and has advanced towards N8. It can be concluded that the valve selection logic for flushing is ineffective in this case. Therefore, it was decided to add the (3.7) restriction. The subsequent scenario will demonstrate this change. At $t = 125s$, it is evident that valve AV7 begins to close. After a period of time, when it has closed sufficiently, the system returns to its initial values.

6.3 Scenario 1.2

As stated in Chapter 4, the initial states remain the same for this scenario, so let us use the model with the additional constraint (3.7) and proceed to present and explain the results. Refer to Figure 6.5 for the specific flow diagram.

Figures 6.6 and 6.7 show the moment before contamination onset at $t = 40s$ and the moment when valves V8 and V9 are completely closed and AV7 starts to open at $t = 70s$. Currently, there are no changes or additional details to report. The situation remains the same as in the previous scenario.

The time $t = 87$ shows differences. Initially, only the V8 valve is opened, and since there is no sensor at L8, we can calculate the flow by examining the values of FI3 and FI5. At this point, the calculation would be $1.3 - 0.4 = 0.9$. Prior to this point, the flow was higher in FI5

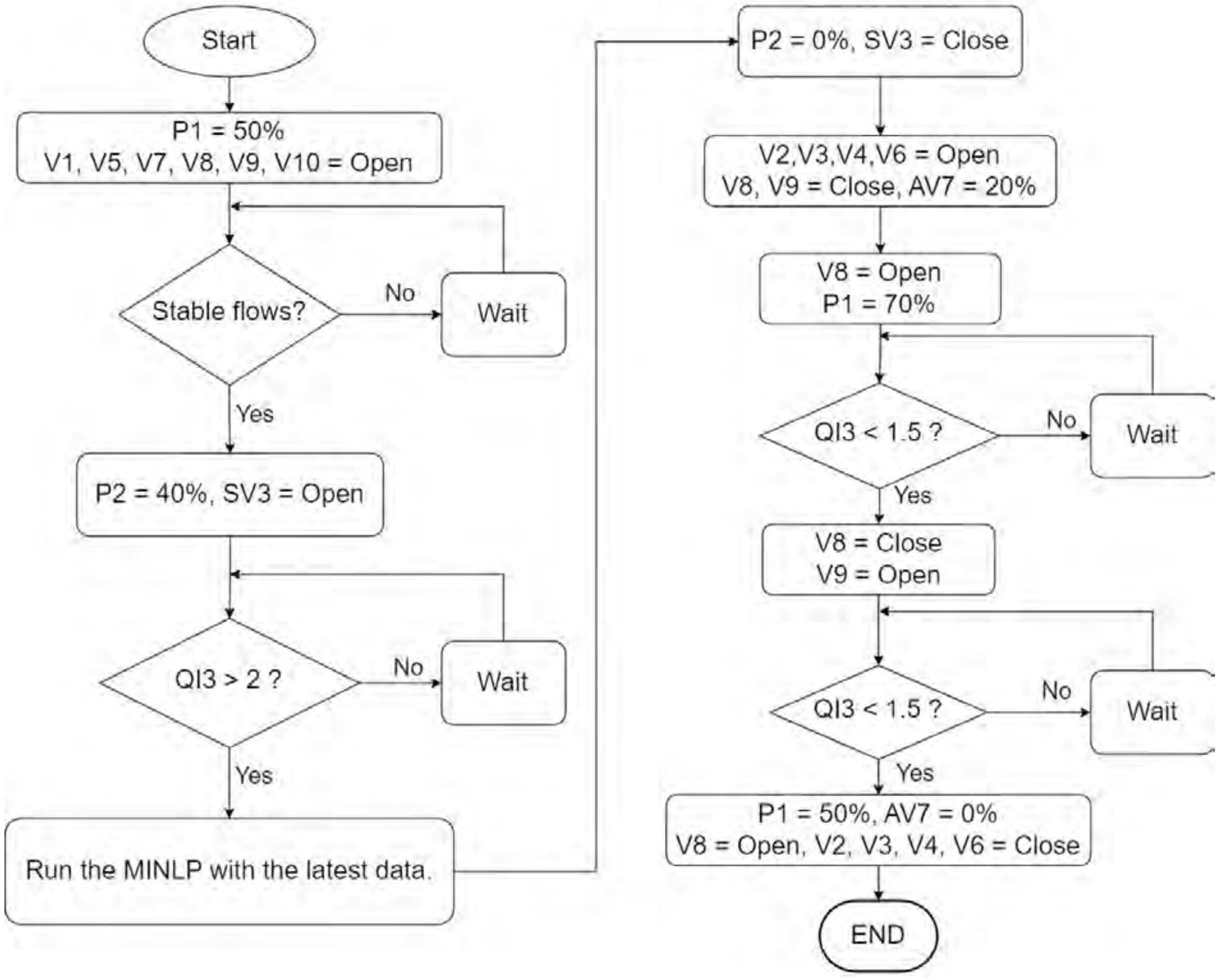

Figure 6.5: Flowchart Scenario 1.2

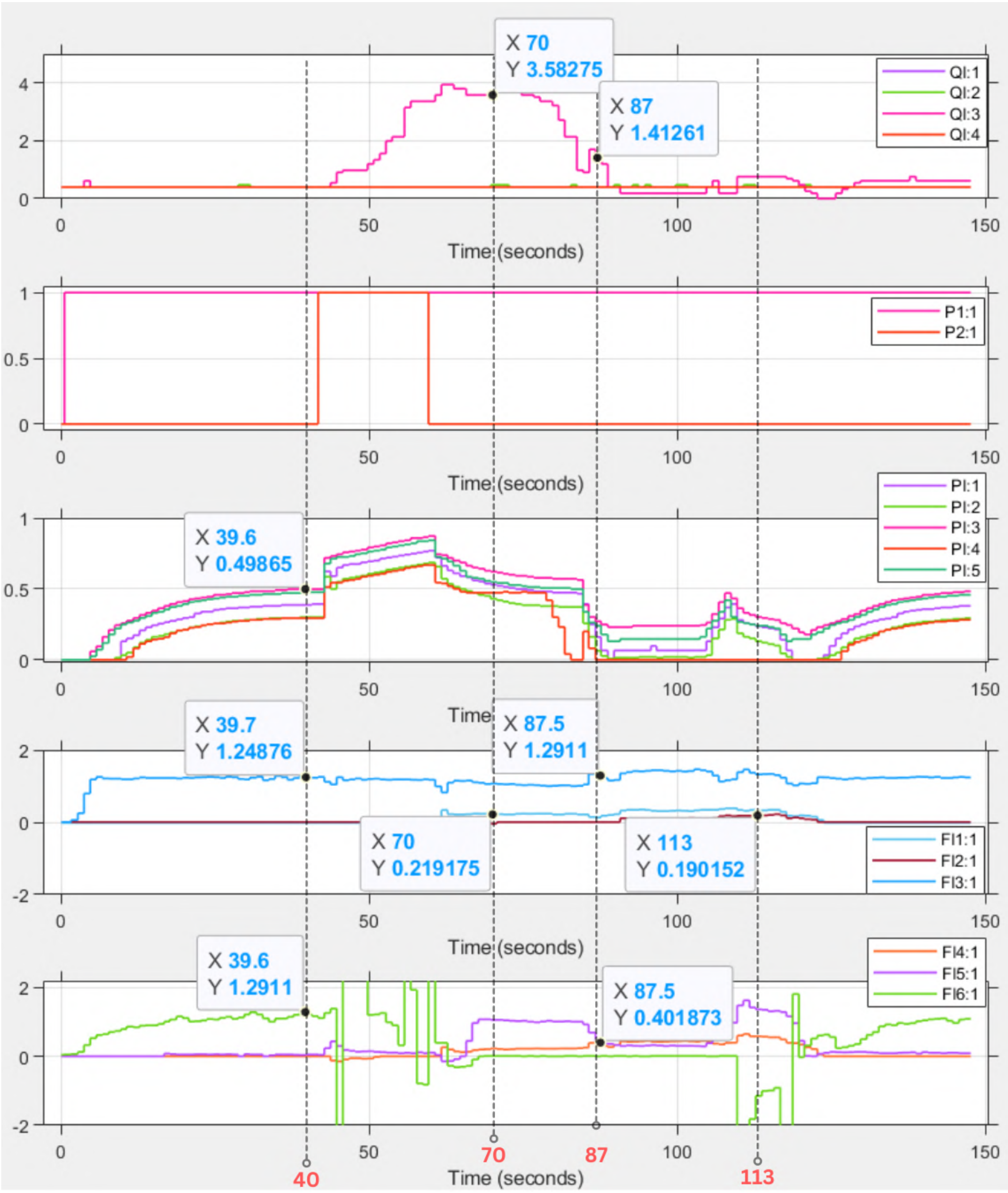

Figure 6.6: Scenario 1.2: Results 1

due to the closure of V8. As a result, all the flow from pipe L5 passed through L7. Currently, only 0.4 LPS passes through L7, while the remaining flow goes through L8 for flushing.

In $t = 113s$, it is observed that valve V8 is already closed and valve 9 is open. When examining the flow, a negative flow is indicated by FI6. Although there are some false readings, this is due to the abrupt changes in the direction of the water flow.

The conclusions that can be drawn from this case are that the second model, with the additional constraint, ensures an adequate flushing stage, as long as there are valves in the pipes adjacent to the pollution node.

Next, the results of scenario 2 will be analyzed.

6.4 Scenario 2

Now the results of Scenario 2 will be explained, they are first shown and explained in 4.21 and here the flushing stage is also added. Refer to Figure 6.8 for the specific flow diagram.

Figure 6.9 shows that the system is in a steady state at the first point $(t = 40.0)$. Although the exact demands at N6 and N8 are unknown, it is confirmed that both add up to approximately 1 LPM (incoming flow to node N6 measured by FI4). This is because the demand at N5 is equal to the flow at L8, which is equal to the flow at L9. In this case, the flow at L9 is negative due to the direction, and this is read by FI6 as 0.2 LPM.

The contamination stage begins approximately 20 seconds after this point. During this stage, the model's results are obtained and applied, and the valves take a moment to close. The second point is shown at $t = 75.0$, where it is observed that valve AV7 is just beginning to open, but the pressures have not yet abruptly decreased. Additionally, it is noted that FI6 is equal to 0, and flows can be seen in pipes L5 and L7. Subtracting $q_5 - q_7$ allows us to determine that the demand at N5 is being met by 0.4. For the demands at N6 and N8, the total is $q_7 + q_4$, which is FI5+FI4 and gives us approximately 1.1 LPM. This proves that the demands are being met and

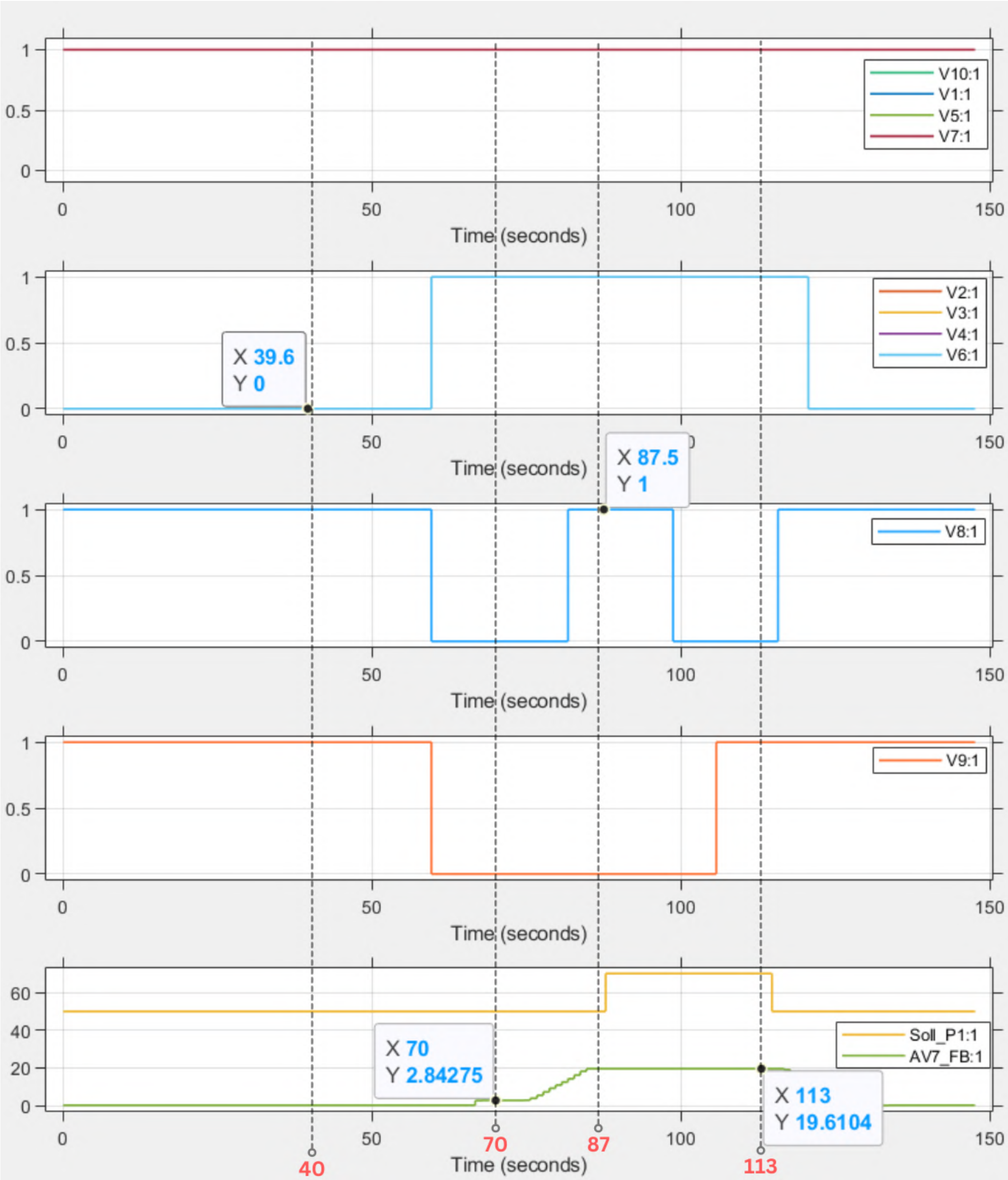

Figure 6.7: Scenario 1.2: Results 2

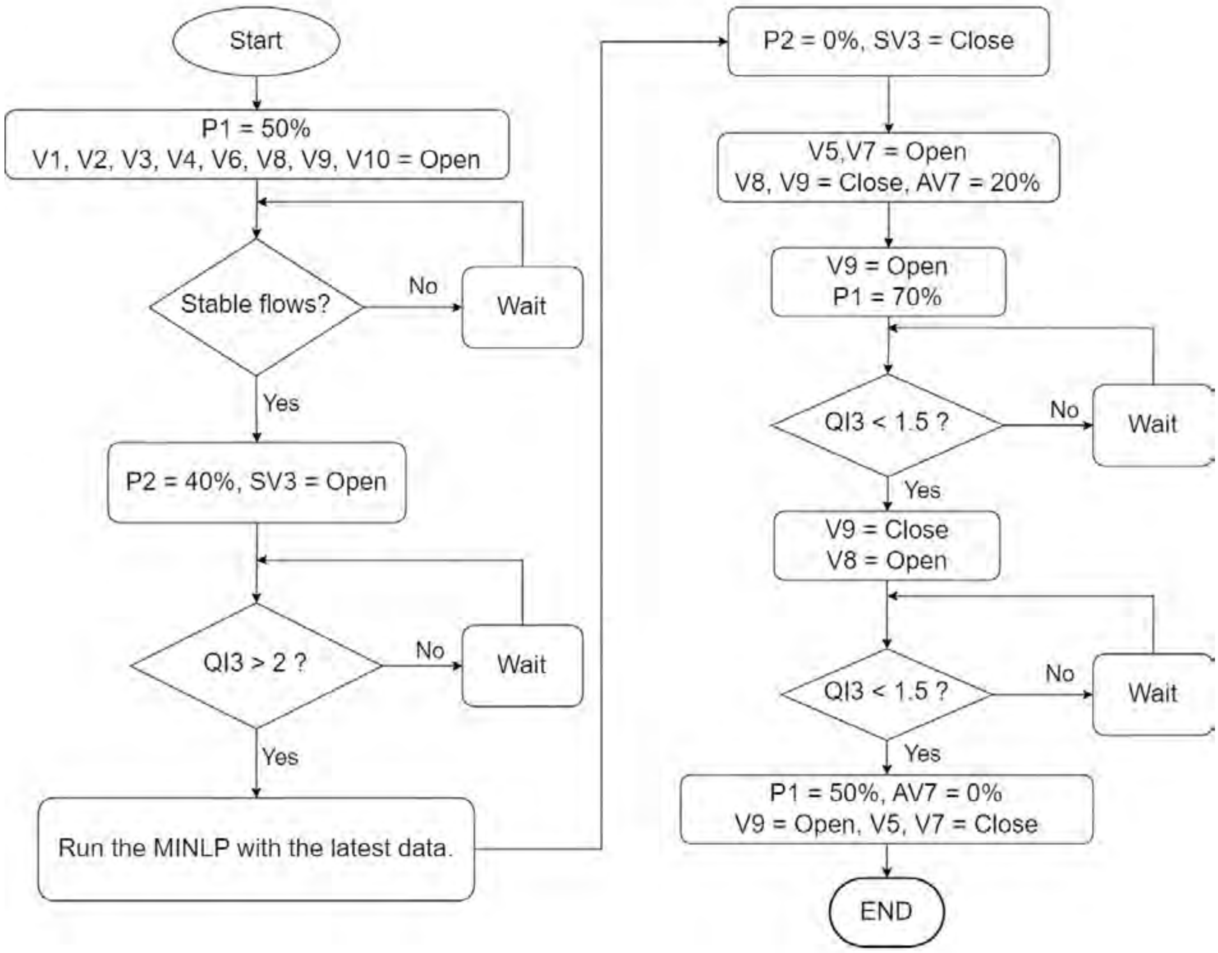

Figure 6.8: Flowchart Scenario 2

the contamination has been isolated.

Figure 6.9 shows a significant reduction in contamination at $t = 80$, indicating that AV7 is open enough to allow contaminated water to flow out. However, the flows and pressures remain stable. V9 is commanded to open for flushing, but it takes approximately 7 seconds to open, so the pressures and flows remain unchanged. At the second point of this figure ($t = 100$), the system is in the middle of the flushing stage of pipe L9. It is evident that the flow q_9, as read by FI6, is negative (-0.8). Despite increasing the power of the pump, the flow that comes out of the demands in N5, N6 and N8 is still sufficient, but it has dropped slightly due to the flushing stage. The values measured by the sensors indicate that approximately 0.2 LPM is maintained in N5, but for N6 and N8, the sum has dropped to 0.8 LPM.

At $t = 125s$, Figure 6.9 illustrates the flushing of pipe L8. The flows measured by the sensors indicate that there is no flow in L9, as the valve is closed. The exact flow that cleans pipe 8 is unknown, but it can be estimated to be at least $q_5 - q_7$, which is equal to FI3-FI5 = 1.2. As the demand in N5 was 0.2 in previous points, an approximate value of 1 LPM can be assigned to the flow passing through L9. It is important to note that the demands are pressure-dependent, so the flow leaving N5 may be slightly higher in this case. The demands at nodes N6 and N8 have been met, as confirmed by the FI4 and FI5 sensors which together provide a flow rate of 0.8 LPM. Although slightly lower than the initial steady state, it is sufficient, representing over 60% of the initial flow. At the second point (t=146.0 s), the initial steady state was observed to have returned with a contamination level of 0.7, which falls within the acceptable range.

The analysis of the results is now complete, leading to the final chapter which includes conclusions, limitations, and future work.

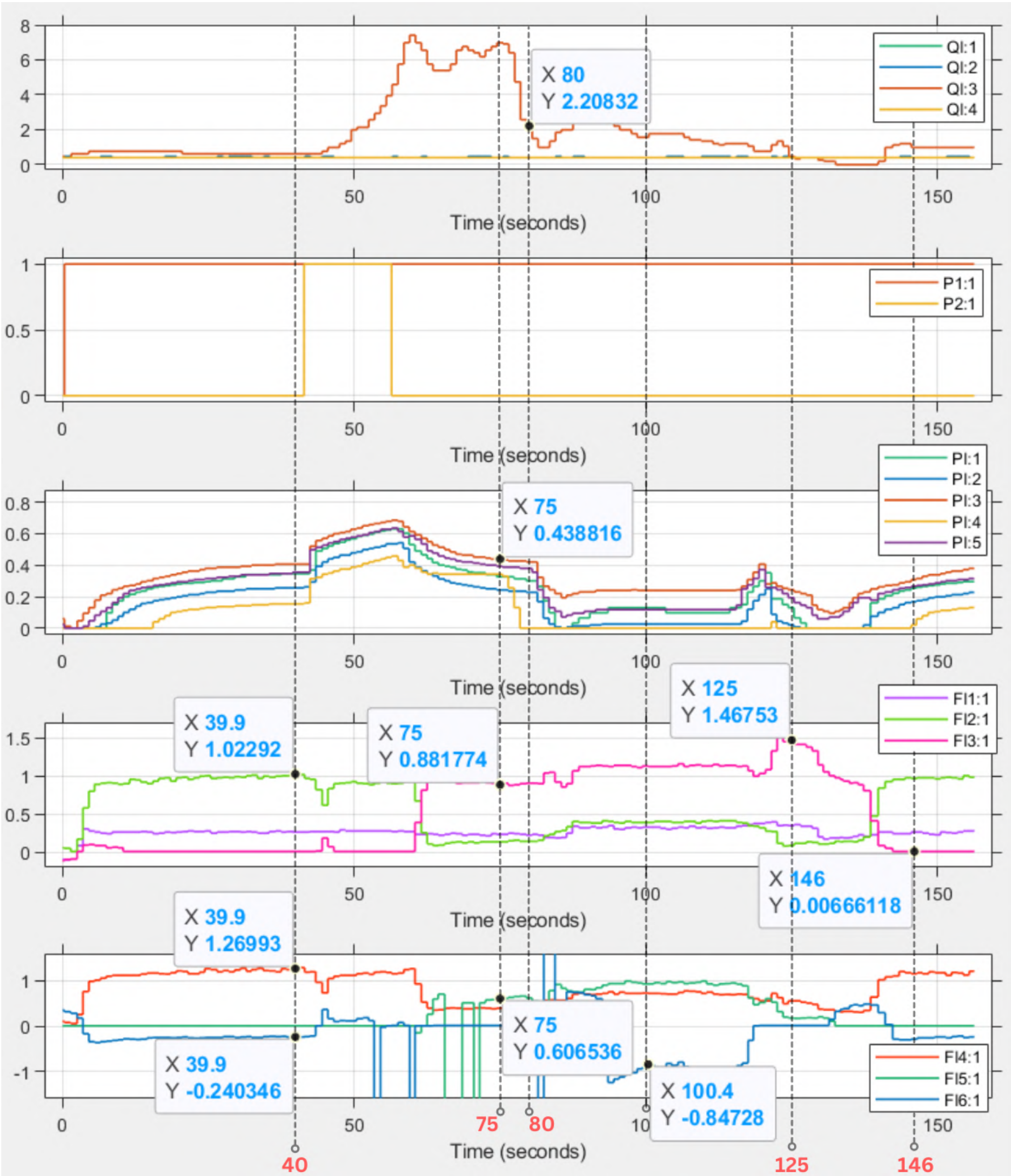

Figure 6.9: Scenario 2: Results 1

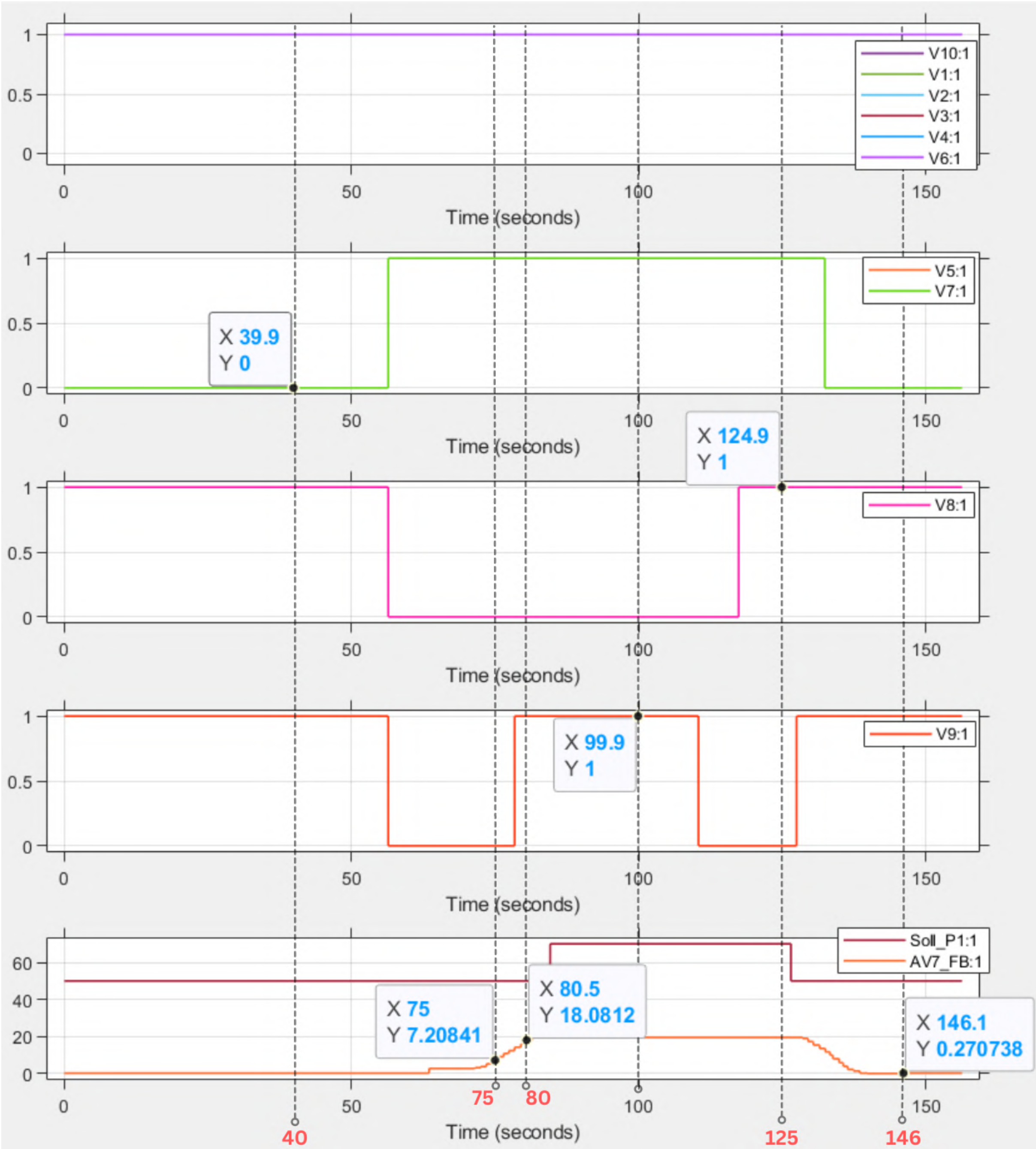

Figure 6.10: Scenario 2: Results 2

Chapter VII

Conclusions, limitations and future work

This chapter will address the conclusions, limitations of the research and potential future work,

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7.1 Conclusions

Based on the research and analysis conducted, it can be concluded that the implementation of the proposed MINLP model is a significant advancement in automating contamination management within WDSs. The model addresses the pressing need for automated strategies in response to the evolving risks of water contamination. It streamlines decision-making processes and enhances the system's resilience against various threats. This aligns closely with the imperative of ensuring global access to clean drinking water.

In summary, the implemented model has successfully achieved its primary objective of autonomously isolating contamination within a defined area. Although the flushing process encountered some challenges, the introduction of an additional constraint significantly improved this aspect. However, there are still some considerations that require further investigation. The empirical validation carried out in a real-world testbed demonstrates the practical and automated feasibility of the model. This was made possible by using Programmable Logic Controllers (PLCs) and sophisticated software capable of managing and resolving the MINLP model. The observation of contamination isolation and evacuation in real-time represents a significant milestone towards the potential global deployment of such systems within Water Distribution Systems (WDS). These empirical insights contribute to the scholarly discourse on water system management and resilience, providing a foundation for future research on refining and expanding the applicability of automated contamination mitigation strategies within WDSs globally.

7.2 Limitations and future work

This research is limited to implementing and validating the model on two simulated systems and on the real system of the Technical University of Ilmenau. Only Bonmin was used as solver, following previous investigations by [8] and [7], but other solvers may be tested in the future. Our model assumes ideal two-way valves, which do not leak water when closed or lose pressure (energy) when open. Another important assumption is that the proposed demand is fixed, meaning it does not change with variations in system pressure.

The validation of the solution was achieved by establishing communication between Matlab and the GAMS software: Matlab provided the necessary data so that GAMS could execute the algorithm solving the MINLP problem, and then Matlab collected the solution data. However, this communication cannot be established in real time using Simulink because it does not support the necessary toolbox functions. The problem's solution delay was simulated as a waiting time equal to the time GAMS took to find an optimal solution.

During testing, it was discovered that the V1 valve was not functioning correctly when testing scenario 3, rendering the results invalid. Additionally, the conductivity sensors at the nodes are not fully in contact with the moving water, leaving a small gap where water can be at rest. Some sensors are also not levelled correctly, resulting in standing water that may be contaminated and giving false readings. The simulations did not consider pressure-dependent demands, whereas the demands in the test bed were pressure-dependent. Nevertheless, the model performed adequately. It is important to note that we cannot guarantee 100% of the original flowrate per node of the demand. This work ensured that at least 65% of the original demand flow was met. One way to improve this is by increasing the pump output during flushing.

It is important to note that some constraints were relaxed to avoid unfeasible solutions. The testbed used for the tests was relatively small compared to real systems. Therefore, it was always possible to find proper solutions. However, in the case of larger systems, it is necessary to investigate what actions can be taken if unfeasible solutions arise. Some ideas could be to try different solvers or software.

As a second point, it is proposed to conduct research on implementing a method for running the solver from Simulink in real-time, rather than manually. According to the software's documentation, the required functions are not supported by Simulink. However, there may be alternative methods to achieve this, such as using a different software to solve the MINLP problem instead of GAMS, or using a different software to control the test bench.

During testing, one obstacle that may arise is the solver taking too long to find an optimal solution. This delay could result in contamination reaching other nodes, making it necessary to increase the isolation zone. Depending on the time it takes to find an optimal solution, this can be achieved by modifying the model or creating a new one specifically for these occasions. Depending on the time it takes to find an optimal solution, this can be achieved by modifying the model or creating a new one specifically for these occasions. It is important to validate this model in scenarios where contamination cannot be completely isolated. The model can provide a solution to minimize the entry of contaminated flow into the system, which could be a viable option in some cases instead of doing nothing or completely cutting off the water supply. It is important to note that this is a theoretical model and its practical application may have limitations. During the pipeline flushing tests, it was discovered that the process is more complex than initially thought. A dedicated study is required for this stage, especially if there are no valves in the pipelines adjacent to the contamination node. This is analysed in scenario 1.2 of case study 2, the test bed.

Finally, a dedicated study is necessary to optimise the flushing of pipes affected by contamination. This may require the development of a separate MINLP model that considers parameters such as the length of the affected pipes, the flow rate, and the duration of exposure to contamination. The model should also determine which valves to open or close, in what sequence, and for how long.

Bibliography

[1] H. Mala-Jetmarova, N. Sultanova, and D. Savic, "Lost in optimisation of water distribution systems? a literature review of system design," *Water*, vol. 10, no. 3, 2018.

[2] N. J. Ashbolt, "Microbial contamination of drinking water and disease outcomes in developing regions," tech. rep., Australia, 2004.

[3] L. Cozzolino, C. Mucherino, D. Pianese, and F. Pirozzi, "Positioning, within water distribution networks, of monitoring stations aiming at an early detection of international contamination," *Civil Engineering and Environmental Systems*, vol. 23, no. 3, pp. 161–174, 2006.

[4] E. Z. Berglund, J. E. Pesantez, A. Rasekh, M. E. Shafiee, L. Sela, and T. Haxton, "Review of modeling methodologies for managing water distribution security," *J Water Resour Plan Manag*, vol. 146, pp. 1–23, June 2020.

[5] C. Bragalli, C. D'Ambrosio, J. Lee, A. Lodi, and P. Toth, "On the optimal design of water distribution networks: a practical minlp approach," *Optimization and Engineering*, vol. 13, pp. 219–246, Jun 2012.

[6] H. D. Sherali and E. P. Smith, "A global optimization approach to a water distribution network design problem," *Journal of Global Optimization*, vol. 11, pp. 107–132, Sep 1997.

[7] H. Hijazi, P. Bonami, G. Cornuéjols, and A. Ouorou, "Mixed-integer nonlinear programs featuring "on/off" constraints," *Computational Optimization and Applications*, vol. 52, pp. 537–558, Jun 2012.

[8] F. Pecci, E. Abraham, and I. Stoianov, "Penalty and relaxation methods for the optimal placement and operation of control valves in water supply networks," *Computational Optimization and Applications*, vol. 67, 05 2017.

[9] B. J. Eck and M. Mevissen, "Quadratic approximations for pipe friction," *Journal of Hydroinformatics*, vol. 17, pp. 462–472, 12 2014.

[10] F. Pecci, E. Abraham, and I. Stoianov, "Quadratic head loss approximations for optimisation problems in water supply networks," *Journal of Hydroinformatics*, vol. 19, pp. 493–506, 04 2017.

[11] P. Bonami, L. Biegler, A. Conn, G. Cornuéjols, I. Grossmann, C. Laird, J. Lee, A. Lodi, F. Margot, N. Sawaya, and A. Wächter, "An algorithmic framework for convex mixed integer nonlinear programs," *Discrete Optimization*, vol. 5, pp. 186–204, May 2008. Funding Information: Pierre Bonami, Carl D. Laird and Nicolas Sawaya were supported in part by a grant from IBM. Gérard Cornuéjols was supported in part by NSF grant CMMI-0653419, ANR grant BLAN06-1-138894 and ONR grant N00014-03-1-0188. Part of this research was carried out when Andrea Lodi was a Herman Goldstine Fellow in the Department of Mathematical Sciences of the IBM T.J. Watson Research Center, whose support is strongly acknowledged. François Margot was supported in part by a grant from IBM and ONR grant N00014-03-1-0188.

[12] T. Saticiöz, "Aufbau einer versuchsanlage für untersuchung der wasserqualität in wasserversorgungsnetz-tolga saticiöz," Master's thesis, TU Ilmenau, 2022.

[13] R. Helmer, "Water quality and health," *Environmentalist*, vol. 19, pp. 11–16, Mar 1999.

[14] D. F. Shams, S. Islam, B. Shi, W. Khan, B. Gunawardana, M. Saad, M. Qasim, H. A. Javed, S. G. Afridi, M. Naeem, and G. S. Khan, "Characteristics of pipe corrosion scales in untreated water distribution system and effect on water quality in peshawar, pakistan," *Environmental Science and Pollution Research*, vol. 26, pp. 5794–5803, Feb 2019.

[15] G. M. e. Silva, D. F. Campos, J. A. T. Brasil, M. Tremblay, E. M. Mendiondo, and F. Ghiglieno, "Advances in technological research for online and in situ water quality monitoring;a review," *Sustainability*, vol. 14, no. 9, 2022.

[16] A. P. H. Association, *Standard methods for the examination of water and wastewater*, vol. 6. American Public Health Association., 1926.

[17] H. B. Glasgow, J. M. Burkholder, R. E. Reed, A. J. Lewitus, and J. E. Kleinman, "Real-time remote monitoring of water quality: a review of current applications, and advancements in sensor, telemetry, and computing technologies," *Journal of Experimental Marine Biology and Ecology*, vol. 300, no. 1, pp. 409–448, 2004. VOLUME 300 Special Issue.

[18] O. Awe, S. Okolie, and O. Fayomi, "Optimization of water distribution systems: A review," *Journal of Physics: Conference Series*, vol. 1378, p. 022068, dec 2019.

[19] N. V. Sahinidis, "Mixed-integer nonlinear programming 2018," *Optimization and Engineering*, vol. 20, pp. 301–306, Jun 2019.

[20] P. Belotti, C. Kirches, S. Leyffer, J. Linderoth, J. Luedtke, and A. Mahajan, "Mixed-integer nonlinear optimization," *Acta Numerica*, vol. 22, p. 1–131, 2013.

[21] G. K. Batchelor, *An Introduction to Fluid Dynamics*. Cambridge Mathematical Library, Cambridge University Press, 2000.

[22] B. J. Eck and M. Mevissen, "Quadratic approximations for pipe friction," *Journal of Hydroinformatics*, vol. 17, pp. 462–472, 12 2014.

[23] F. Pecci, E. Abraham, and I. Stoianov, "Quadratic head loss approximations for optimisation problems in water supply networks," *Journal of Hydroinformatics*, vol. 19, pp. 493–506, 04 2017.