**People's Democratic Republic of Algeria**

**Ministry of Higher Education & Scientific Research**

**Yahia Fares Medea University**



**Faculty of Sciences**

**Department of Mathematics and Computer Science**

**Master's Thesis**

**Specialty:** Computer science

**Option:** Systems Engineering and Web Technology

*Theme:*

# Automatic approach implementation for a digital twins development for a drinking water distribution system.

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University Year: 2020-2021

## Appreciation

First of all we thank ALLAH for guiding us and giving us the courage and strength to do this modest work.

We extend our heartfelt thanks to our promoter and

coach Mr. Mazari Redha for his patience, encouragement and valuable guidance.

Our thanks go to Mr. Rahim Messouad, Research Professor at the University of Medea, his critical eye was very valuable to us in structuring this work and improving its quality.

Our respect to the members of the jury who have agreed to judge this modest work, to bring their scientific reflections and criticisms.

In the end, we would like to express our gratitude to all employers and administration of our university.

**Dedication**

This little effort is dedicated to :

- My parents, who have never failed to encourage and support me. I owe them a debt of gratitude for serving as role models for me in terms of tenacity, optimism, and ambition.
- My sister Imen, and my brothers Mourad and Mohamed Riadh, and my brother-in-law Mohamed, Having them by my side has always made me feel like I'm in the middle of a great family.
- to my nephews Iyed and Mohamed Rassim, and my niece Lina.
- specially to Nour el houda, my memory companion, partner, friend... without her nothing would have been the same. This year has been full of emotions, and I'd like to express my gratitude for your support and the wonderful relationship we've formed.
- to all my colleagues and friends especially "Naziha, Sarah and Nour elhouda".

Finally, I'd want to thank everyone who helped me get this work done in the best possible way, no matter how far away they were.

Inès

**Dedication**

I thank ALLAH who has given me all the will and patience to achieve this work.

I dedicate this modest work:

To my source of sweetness, tenderness, love and affection, and thanks to the encouragement and sacrifices she made, I was able to carry out this work, my dear **M**other.

To my dear **F**ather, for the sacrifices he has made for my education and for the future he has ceased to offer me.

To my two dear **S**isters and my only **B**rother.

To my **H**usband who has supported me, encouraged me, appreciate my efforts and created the favorable environment, the joyful atmosphere and the jovial atmosphere to procure my work

To my dear friends **Ines** & **Naziha**

To All who I know.

Nour El Houda

**Abstract**

A digital twin system is a virtual representation of a real system. Our work is to develop digital twins for drinking water distribution network, we used Epanet for modeling our network and Eclipse Ditto platform for the creation of our digital twins. The main goal of this work is to design and develop a web application aimed at improving the control of the drinking water distribution system in real-time

**Key-words:** digital twin, Eclipse Ditto, Epanet, Water distribution system, web application.

**Résumé**

Un jumeau numérique est une représentation virtuelle d'un système réel. Notre travail est de développer des jumeaux numériques pour le réseau de distribution d'eau potable, nous avons utilisé 'Epanet' pour modéliser notre réseau et la plateforme 'Eclipse Ditto' pour la création de ces derniers. Le but principal de ce travail est de concevoir et de développer une application web visant à améliorer le contrôle du réseau de distribution d'eau potable en temps réel.

**Mots clés :** Jumeau numirique, Eclipse Ditto, Epanet, Système de distribution d'eau, application web.

**ملخص**

نظام التوأم الرقمي هو تمثيل افتراضي لنظام حقيقي. عملنا هو تطوير التوائم الرقمية لشبكة توزيع مياه الشرب، استخدمنا 'Epanet'لنمذجة شبكتنا ومنصة 'Eclipse Ditto' لانشاء التوائم الرقمية لدينا. وهدفنا في هذا العمل هو تصميم وتطوير تطبيق ويب يهدف إلى تحسين مراقبة نظام توزيع مياه الشرب في الوقت الحقيقي.

**الكلمات المفتاحية:** توأم رقمي ،Epanet, Eclipse ditto ,شبكات توزيع مياه الشرب, تطبيق ويب.

# Glossary

| | |
|---|---|
| **IOT :** | **Internet Of Things** |
| **DT :** | **Digital Twin** |
| **HTTP:** | **HyperText Transfer Protocol** |
| **CSS:** | **Cascading Style Sheets** |
| **PHP:** | **Hypertext Preprocessor** |
| **HTML:** | **HyperText Markup Language** |
| **UML:** | **Unified Modeling Language** |
| **JSON:** | **JavaScript Objet Notation** |

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# General introduction

## 1. General introduction

The drinking water system is a very important part of society. The basic function of a water distribution system is to satisfy the needs of users by water. This water must be of good quality that meets the standards of potability and at a pressure.

Access to safe drinking water in sufficient quantity and quality is a key issue for citizens. To avoid the problems that engineers had in their management of drinking water distribution system such as a waste of effort and time looking for particular information, the difficulty of keeping component and network information on up-date also network problems are difficult to identify, as well as the difficulty of collecting real-time information from networks.

Water distribution networks have developed to intelligent water networks in order to improve drinking water service performance while saving energy, conserving water resources, and monitoring the quality of water supplied to customers [1]. As a result of this, this system has become a part of the internet of things (IoT).

The Internet of Things, often known as IoT, is the process of connecting physical items to the internet in order to share, gather, and move data. IoT adds a layer of digital intelligence to the world around us, making it more interesting and responsive without risking the quality of the system [2].

The responsible technology for linking these various items is the digital twin platform.

A Digital Twin is a digital representation of a physical object or system and it is a bridge between the digital and the physical world. The technology behind digital twins has expanded to include large items such as buildings, factories and even cities [3].

We suggest a strategy for the construction of digital twins water distribution systems in this scenario. The goal is to simulate the drinking water distribution system that will be created in order to generate its digital twin, which will eventually be controlled and visualized.

This dissertation is divided into four sections, as shown in:

**CHAPTER 01:** Discussed the internet of things, as well as the digital twin and how it works.

**CHAPTER 02:** Covered the drinking water distribution system and the digital twins in water distribution networks

**CHAPTER 03:** Shown the conception, it gives a thorough and in-depth look at the technological solutions that make this web application possible.

**CHAPTER 04:** Cover the implementation of the application, which allowed the automatic construction of a Digital Twin for a drinking water distribution network.

# Chapter 1:
# Internet of things
# &
# Digital twins

# 1. Introduction

The Internet is a global computer network that is open to the public, composed of millions of private, public, academic, commercial and government networks. The internet has also made it easier for individuals to communicate with one another, thus turning the entire globe into a little village. Since the 2010's, a growing number of different types of objects are connected, forming the "Internet of Things (iot)".

The internet of things is the next step in the digital revolution, billions of common things linked have the potential to make everyday life easier. Those physical things can be represented as digital things, the technology of Digital Twins, different from internet of things and 3D modeling, prevents breakdowns and predicts how different parts of a device will age.

In this chapter we will present the notion of iot and digital twin and understand their characteristics and how to start with a digital twin technology in order to be able to represent a digital twin system.

# 2. Internet of Things

The term Internet of Things is 16 years old only. But the actual idea of connected devices had been around longer, at least since the 70s. Back then, the idea was often called "embedded internet" or "pervasive computing". But the actual term "Internet of Things" was coined by Kevin Ashton in 1999 during his work at Procter & Gamble. And because the internet was the hottest new trend in 1999, he called his presentation "Internet of Things" [4].

## 2.1. Definition

The Iot is the network of physical objects accessed through the internet, these objects contain embedded technology to interact with internal states or the external environment. In other words, when objects can sense and communicate, it changes how and where decision are made and who makes them [5].

### 2.1.1. Definition of thing

Things are objects of the physical world or of the information world (virtual world) which are capable of being identified and integrated into communication networks.

- Types : Things have associated information, which can be static and dynamic.
  - ✓ **Physical things** : Exist in the physical world and are capable of being sensed, actuated and connected.
  - ✓ **Virtual things** : Exist in the information world and are capable of being stored, processed and accessed., include multimedia content and application software.

**Architecture**

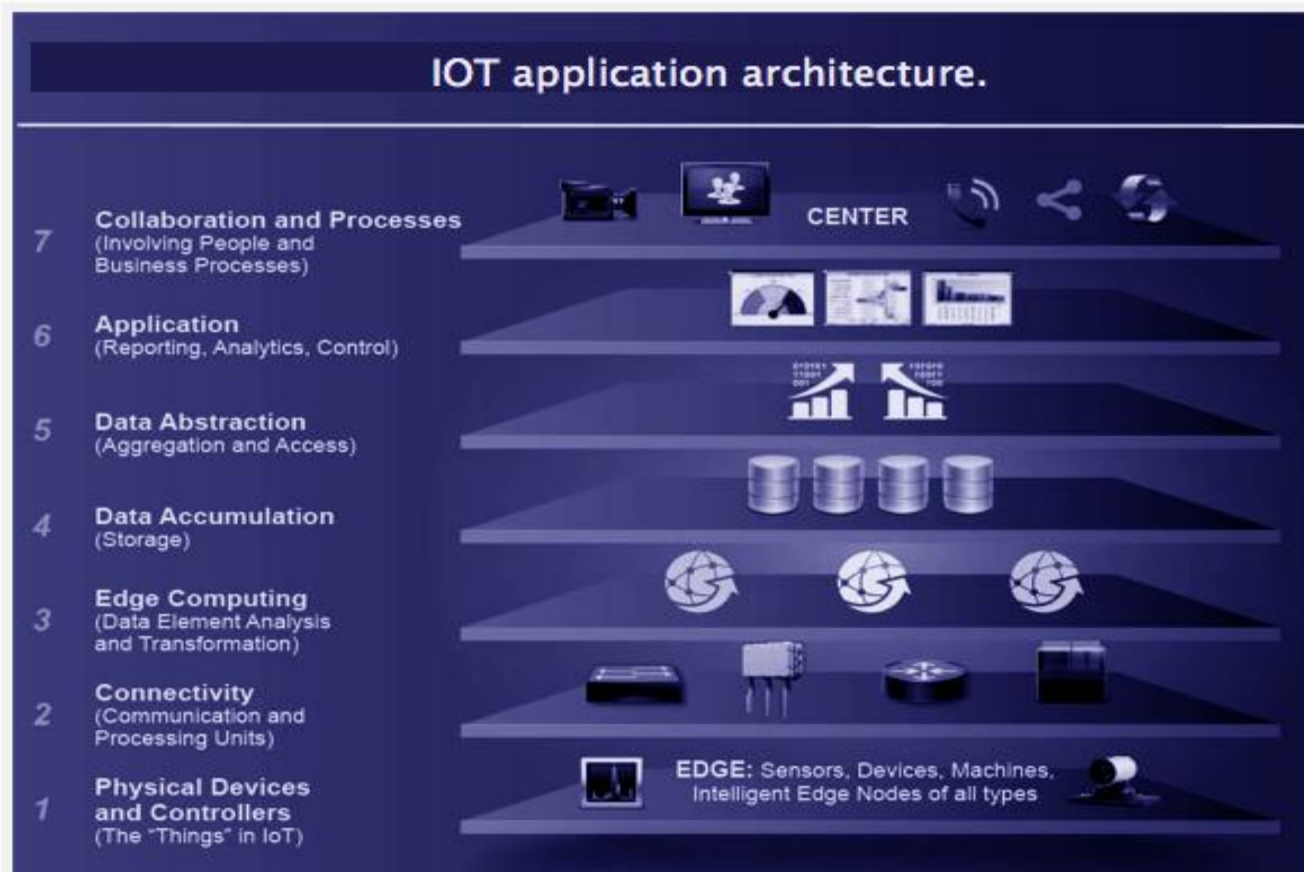



**Figure 1.1 :** The architecture of Internet of Things [6]

1) The lowest & middle a part of iot software is the sensors and electronic gadgets this is in a position to connect with things & grasp the facts from it.
2) Sensor gathers the records however that we need to convert it into understandable format & join the one's sensor device using some protocol that we want to configure right here in the second layer and also clear out statistics i.e. placed a few thresholds on your information for taking smart selection.
3) Network connectivity, join your tool with wi-fi connectivity or net stressed connection. This connectivity is changed based on context & area.
4) We are able to say this sediment as protection layer or software abstraction layer or facts abstraction in which we can apply security to our product. This accretion role should be changeable based on the domain & How we want to apply abstraction to our software.
5) At this level, we are able to persist our good judgment, use this information for taking clever selection or for reporting purpose. That is the important layer, in which our definite product & business common sense comes into the image.
6) This residue wherein we are able to say its presentation layer or choice taken layer. Primarily based on the requirement we will display reviews or applying system

learning or some custom common sense and takes clever choice and ship signal again to the sensors.

7) That is in which our God exists. For whom we're layout this whole product. The consumer engages with this sediment that is the UI layer [6].

## 2.2. Domains

IoT applications are expected to equip billions of everyday objects with connectivity and intelligence [7]:

**2.3.1 Smart Home Applications :** Refers to all of the linked objects that can be contained in a house: wired lamps , smart fridges, thermostats with controlling sensors, and so on. The Internet of Things is bringing the house of the future to life

**2.3.2 Health Care :** In the health sector, the Internet of Things will facilitate the implementation of personal networks for the management and tracking of clinical symptoms. Linked objects will allow for the monitoring of tension, heart rate, and sleep quality, measure the sugar level.

**2.3.3 Smart Cities :** IoT may be used by the government and engineers to study the often-complex factors of community planning that are unique to each city. Water storage, pollution disposal, and emergency situations will also benefit from the use of IoT applications.

**2.3.4 Agriculture :** Smart agriculture to improve the capacity of agricultural systems, contribute to food security by integrating the need for adaptation and mitigation potential into sustainable agriculture development strategies

**2.3.5 Industrial Automation :** With IoT applications, it's also possible to re-engineer products and their packaging for improved cost and consumer service.

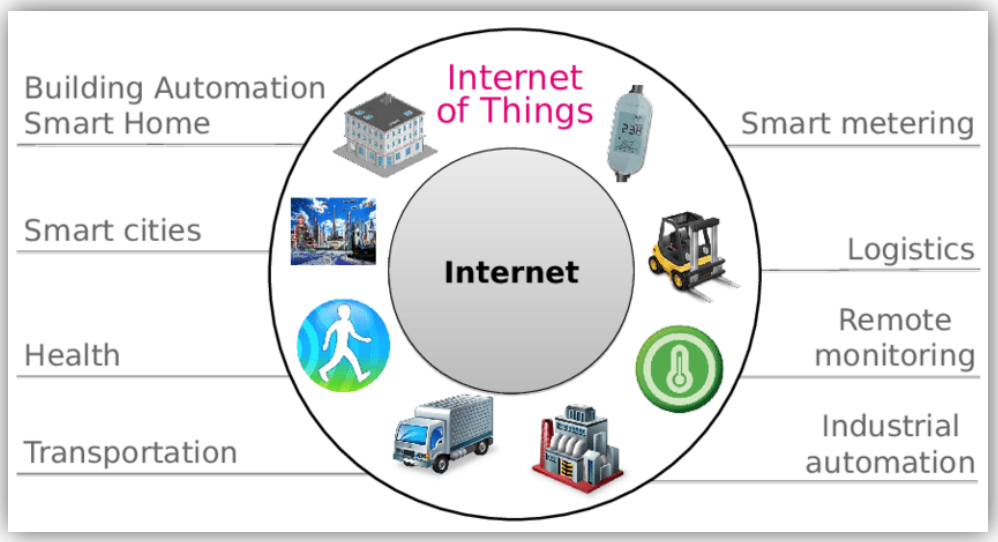



**Figure 1.2**: IOoT domains [8]

### 2.3. Advantages

The advantages of internet of things can be seen in any field of life and industry:

- Access information : Get real time-access to data and information that is stored miles away from your current position.
- Communication: Better communication is possible over a network of interconnected devices, making the communication of devices more transparent, which reduces inefficiencies.
- Cost-effective : Using a connected network to transfer data packets saves time and resources. The same data that used to take a long time to transmit can now be transmitted in a quarter of the time.
- Automation : in an enterprise aims to increase service quality while reducing the amount of human interaction [9].

### 2.4. Disadvantages

There's many disadvantages of internet of things in many fields:

- **Privacy & security:** sensitive information can not be secure and may be easily hacked by third parties.
- **Complexity & Dependability :** In case of a bug in the system this may have a significant impact on the entire system..
- **Lesser jobs :** when any job is automated, the need for human labor would be greatly reduced and this will have a direct impact on employability.

## 3. Digital twin

A digital twin is a computer program that uses physical or system data from the real world to create simulations that can predict how a product or process will behave. Its concept originated from NASA and aims to improve the physical model simulation of spacecraft. This means that digital twins are vital tools that can help engineers not only understand the performance of products, but also their future performance. With this information, organizations can learn more quickly and break the old boundaries around product innovation, complex life cycles, and value creation.

❖ Three main components must be included in a digital twin:

- ✓ Physical objects in real space.
- ✓ Digital twins in the form of software.
- ✓ Data that links the first two elements together.

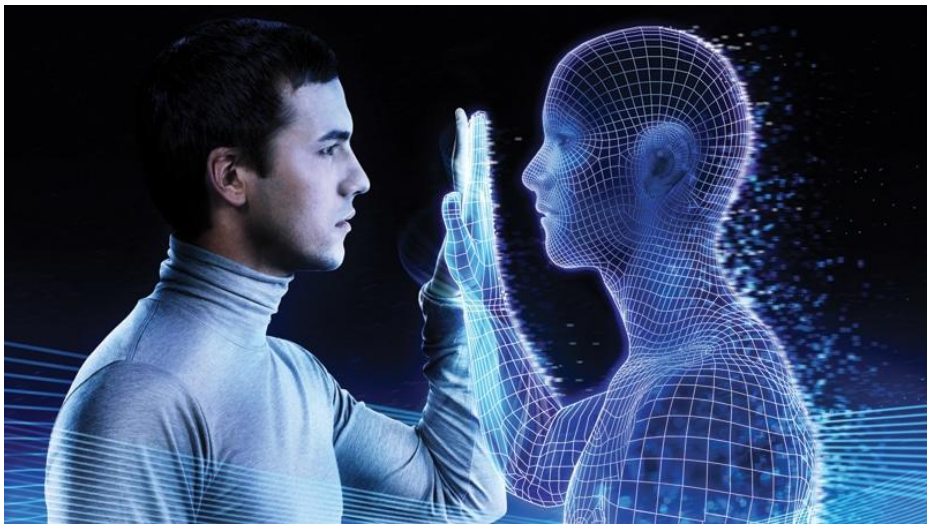


Figure 1.3: Digital Twin

- Digital twins can help manufacturers and engineers complete many tasks, such as:
  - ✓ Real-time visualization of products being used by real users.
  - ✓ Establish digital threads to connect different systems and improve traceability.
  - ✓ Troubleshoot remote equipment.
  - ✓ Manage complexity and links within the system.

## 3.1. How does the digital twin work

The digital twin is a bridge between the physical world and the digital world. It can be processed complex or simple. Different amounts of data determine how accurately the model simulates the physical version of the real world. Its life begins with experts who applied mathematics or data science researching the physical and operational data of real objects or systems in order to develop mathematical models that simulate the original objects [10]. At the same time, his developers ensured that the virtual computer model can receive feedback from the sensors, which collect data from the actual version.

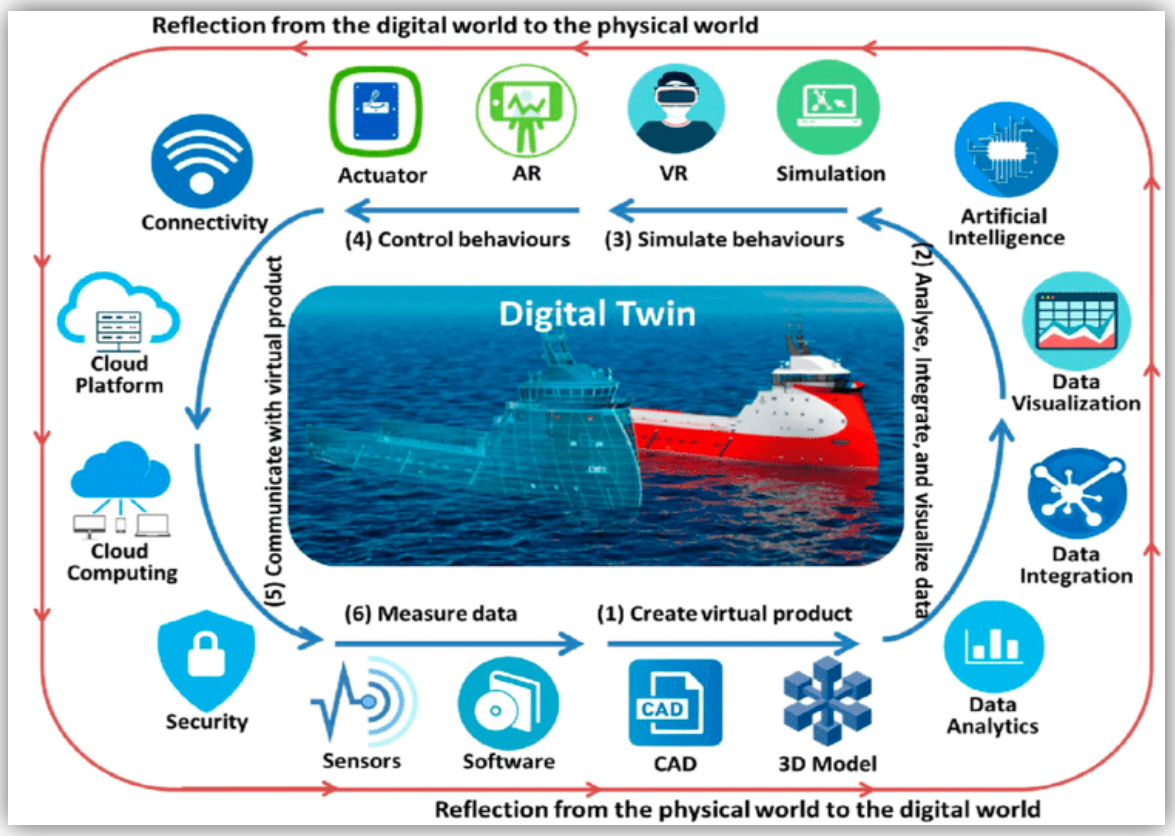



Figure 1.4: Enabling technology of digital twin [11]

In this way, the digital version can simulate what happened to the original version in real time, creating an opportunity to gather insights into performance and any potential problems.

In manufacturing, you can use digital twin technology at various levels [10]:

- Component level-focus on a single highly critical component in the manufacturing process.
- Asset level-create a digital twin of a single device in the production line.
- System level-use digital twins to monitor and improve the entire production line.
- Process level-covers the entire manufacturing process from product and process design and development to manufacturing and production. It is also suitable for the distribution and use of finished products by customers/patients throughout the life cycle, as well as the development of future products.

### 3.3.1. How to start with a digital twin technology ?

When a water utility is interested in starting to use Digital Twin technology, there are several key aspects to take into consideration:

i. **Define your goals:**

By answering these questions: Why do we need a Digital Twin? What are we going to use it for? What will be the advantages for the organization? And the answers are the best starting point for adopting the technology, as it has an impact on how it should be introduced and configured.

ii. **Analyse the starting point :**

Before adopting a Digital Twin, it is also important to be aware of the types of digital information that are presently available in the company and to identify the measures that need to be taken.

iii. **Control the evolution of the project :**

To evaluate the development of Digital Twin activities, multiple milestones and indicators must be defined. Organizations may deploy technology with more confidence if checks and balances are included [12].

### 3.2. The benefits of digital twin

The benefits of digital twin differs depending when and where it is used [13][14]:

- ✓ Using digital twins to monitor existing products such as wind turbines or oil pipelines can reduce maintenance burdens and save millions of dollars in costs.
- ✓ Digital twins can also be used for prototyping before manufacturing, thereby reducing product defects and shortening the time to market.
- ✓ Reduce risks in various fields, including product availability and market reputation
- ✓ increase profit
- ✓ Improved product quality and enhanced your insight into product performance in multiple realtime applications and environments
- ✓ Reduce maintenance costs by predicting failures before they occur.

However, in terms of all benefits, digital twins are not suitable for all situations because it adds complexity. Some business problems do not require a digital twin at all, and can be solved without the associated time and cost investment.

## 4. Conclusion

In this chapter we attempted to clarify the concept of the Internet of Things, and their uses in different domains in life, we also identified the Digital Twins and how it works.

Digital Twins can be useful in a vital area such as drinking water distribution networks, which we will see in the next chapter.

# Chapter 2:
# Drinking water distribution networks.

# 1. Introduction

Water distribution networks carry drinking water from a centralized treatment plant to consumers' taps.

The aim of this chapter is to talk about this network, its different resources and highlight how digital twins can help the water industry to improve performance of its infrastructure.

# 2. Drinking water distribution networks

## 2.1. Definition

A drinking water system is a set of pipes and equipment organized to allow the circulation and distribution of drinking water to consumer with appropriate quality, quantity and pressure [15].

## 2.2. Different types of water Resources

Turning on the valve can provide you with the water you need, but this is not where your water comes directly. Water resources occupy a special place among other natural resources. Water is the most widely distributed substance on our planet.

These are the various forms of water sources found around the world, and how they impact what comes out of your sink:

### a. Surface-water Resources

Rivers, dams, ponds, reservoirs, and wetlands all fall under this category because they contain fresh water instead of saltwater. Since these sources are the simplest to clean, they provide the best drinking water for the general population [16].

### b. Ground-water Resources

Water is found under the ground surface in pores and gaps in the soil, and is collected by drilling wells. But because of how difficult it is to access these resources, we hardly get to use them [16].

### c. Storm-water Resources

Storm-water or 'rain-water' is a reasonably pure water supply, can also be used for potable purposes. It is also a free resource that can be obtained in vast numbers from roof catchments and other surface areas and used for a number of purposes [17].

### d. Waste-water Resources

Wastewater is another type of water source in the world. This is the water we use for our household, manufacturing, and agricultural activities; it's then disposed of through our local sewage systems

## 2.3. Infrastructure

Distribution system infrastructure is generally considered to consist of the pipes, pumps, valves, storage tanks, reservoirs and other hydraulic appurtenances that connect treatment plants or well supplies to consumers' taps [18].

a. **Pipes:** is a tube designed to transport drinking water from the source to the customer [18].



Figure 2.1: Pipes

b. **Tanks & Reservoirs:** are containers that hold and store the treated water for supplying during every day usage, emergencies (such as during fires, repairs, etc.) and also to help in absorbing the hourly fluctuations in the normal water demand. Exists in 4 types :

- Underground reservoirs.
- Small ground level reservoirs.
- Large ground level reservoirs.
- Overhead tanks.



Figure 2.2: Tanks and Reservoir

c. **Pump:** is a device that expends energy in order to raise, transport, or compress fluids.



Figure 2.3: Pump

d. **Valves:** in water system valves are used to control the quantity and direction of water flow



Figure 2.4: Valve

e. **Junctions:** the intersection of pipes that transfer water from one place to another.



Figure 2.5: Junction

### 2.4. Smart water networks

A smart water system is an important collection of items, solutions, and applications that allows communities to manage and solve issues directly, automatically and identify the main problem and use data to improve all facets of the water delivery network by using intelligent measuring instruments (sensors, flowmeters) [19].

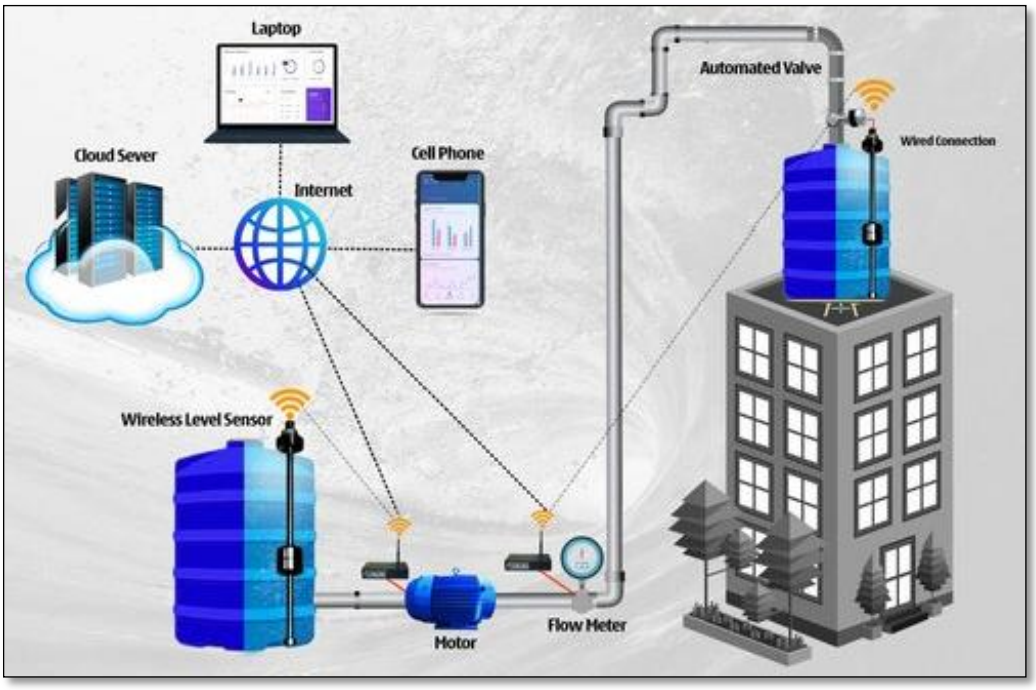



Figure 2.6: Smart water network system[20] .

## 3. Digital twins in water distribution networks

Digital twins are being used to develop the management of water distribution systems, also will allow for improved system performance, efficasity and help to reduce risks, as well as the early warning and informed response to emergencies, which will help the operators to make quick and effective decisions and allow to detect quality weaknesses throughout the network and to find the best strategy for their improvement [20].

### 3.1. The 5 components of the digital twin for water

The deployment of information and communication is allowing water systems to become intelligent. This due to the following five components:

**a. Geospatial and physical data about the assets in the system:**

For water and wastewater utilities, this usually starts with a Geographic Information System, this mapping system can be vertical assets like pumps and tanks, or horizontal like pipes, and it provides a complete picture of what exists and where it is located. A Digital Twin will highlight the relative location and how one resource affect another when examining the physical data about these assets.

**b. Direct observation or sensor data about the affecting environment:**

After the physical features of the networks have been determined, we may combine data about the environment that impacts the asset – these data are the inputs that change asset and relational behavior.

**c. Performance data:**

Can be stored as static data and the more historical performance data that exists, the better we will be able to replicate the asset's behavior

**d. The analytics:**

The analytics are the driving force behind the Digital Twin's ability to recreate real-life scenarios. Create superior hydraulic, hydrological, and water quality analysis numerical engines

**e. Digitalization:**

A useful digital twin need to visualize and translate the result to digital data.

## 3.2. Digital twin's value for water distribution networks

Water utility operators benefit from digital twins:

- ✓ Virtually test new equipment or control sequences without risking real-world operations.
- ✓ Safer responds is a such way, before travelling to the location, make a quick analysis of possible solutions.
- ✓ Collaborate across engineering, planning and operations for better and faster decisions.
- ✓ Train to work with the system in the most effective and safe way possible to compile and display the valuable collected data for optimal system performance.
- ✓ Predict the future using data analytics and computer model simulations for planning (what-if scenarios), to respond intelligently to pipe breaks and to handle crises [22].

### 3.3. Methodology for the automatic development of digital twin

The digital twin will facilitate and leverage quick changes and long-term impacts on the manufacturing plant. Users can apply these methodology's steps to implement digital twins in their manufacturing plant:

i. Collecting static and dynamic knowledge. Static knowledge includes geometrical dimensions, bill of materials, etc. The dynamic information is the one that changes with time along the product life cycle.
ii. Designing a conceptual model by representing the physical processes in the manufacturing plant. It will enable the exchange of information of the problem attributes in the virtual world.
iii. Data requirement decides which data should enter into the Digital Twin, and it can be used as a foundation for digital twin. This step takes physical properties with sensors that measure critical inputs.
iv. Data should be communicated by exchanging different functions using a number of technologies, such as network communication, cloud computing, and network security.
v. Building the digital twin by modeling input and output factors, such as material flow, time, product output, etc. The data should come from the real plant.
vi. The user executes the digital twin model, and the output provides feedback to the user, so that users can make an informed decision. The performance can be evaluated, and different scenarios can be tested and detect any problem if it existed [23].

## 4. Conclusion:

In the second chapter we talked about drinking water distribution networks and how digital twin has arrived in the water industry. The aims is to help utilities, better understand its benefits and make its adoption easier.

Like every system, water networks may also face problems which cost money, materials and time. Our goal is to develop an application to monitor and control in real time with detection of these problems before they happened.

The following chapter will present the conception of the application for the automatic construction of a digital twin for the drinking water distribution network.

# Chapter 3:
# Conception

## 1. Introduction

In this chapter we discuss the concept of our work, which consists of building and developing an application based on digital twins to supervise and monitor the water distribution network.

## 2. Project building steps

### 2.1. The proposed architecture

Figure 3.1: represents the transformation architecture from physical to digital twin part using node-red

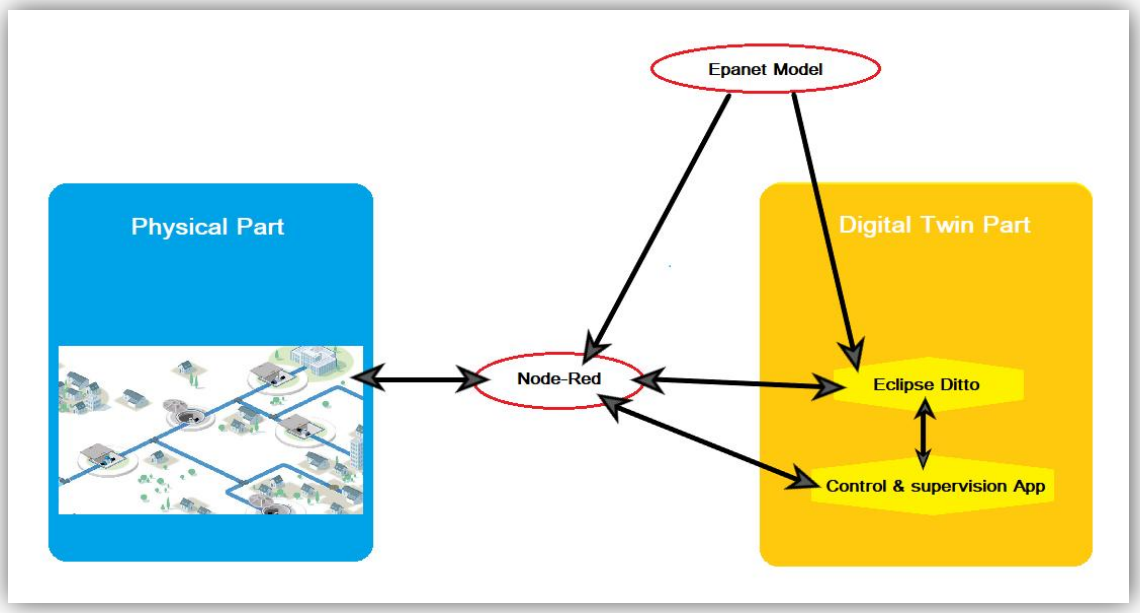



**Figure 3.1:** Transformation from reality to digital twin

### 2.2. Modeling a water distribution network

A model is a representation of reality, a problem or an idea. So, a model is never an exact reproduction, but rather a simplified version of the original system. A model for water distribution network can help to represent digital twins of this network's components in order to be able to operate on reality.

In our work we used Epanet, software that is used by engineers and consultants to model and simulate water distribution networks. It was created with the aim of understanding the flow and destination of drinking water, with Epanet we can create, edit and export water network distribution model [24].

The figure 3.2 represent a model of water distribution network using Epanet

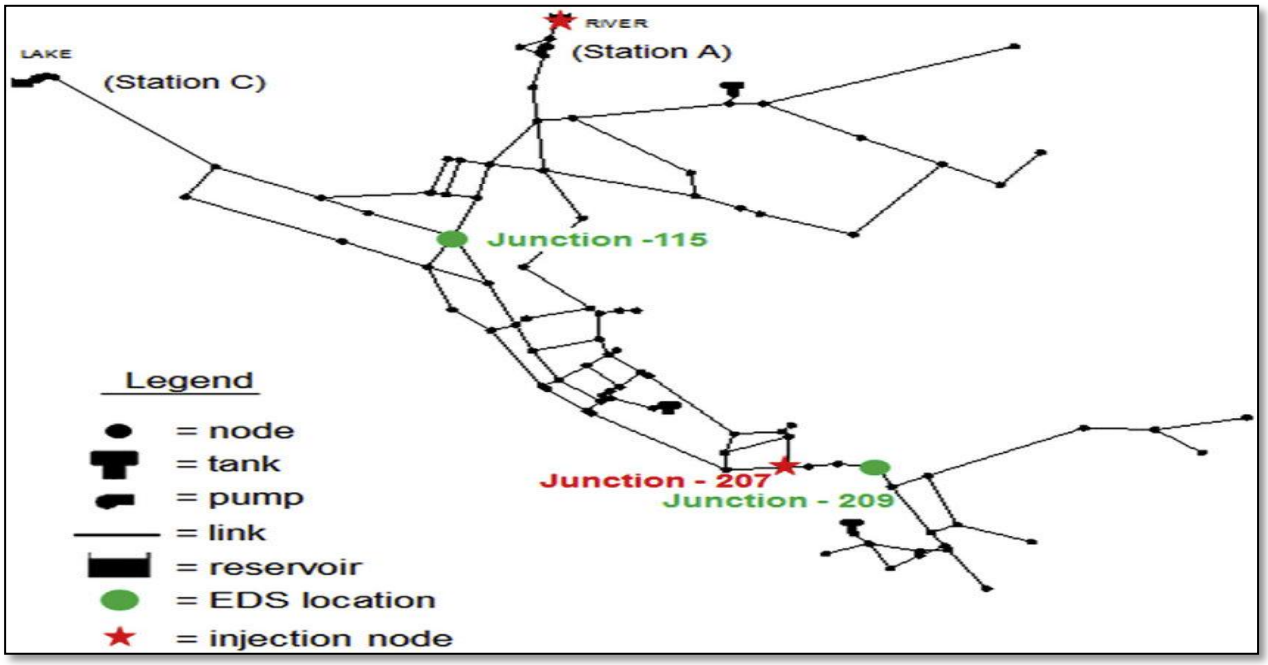



Figure 3.2: Model of water network using Epanet [24].

## 2.3. Digital twin creation

A digital twin design is made by gathering data and creating computational models to test it. This can include the interface Eclispe Ditto between the digital model and an actual physical object to send and receive feedback and data in real time [26].

### 2.3.1. Communications type of digital twin

Digital representation of a physical device exists to give indications of the state of that device. Eclipse Ditto approaches this by way of two communication channels: the twin and the live channel [27].

**a) Twin channel**

This channel is connected to the digital representation of a Thing. This Thing is managed with Ditto. This is state and properties can be read and updated.

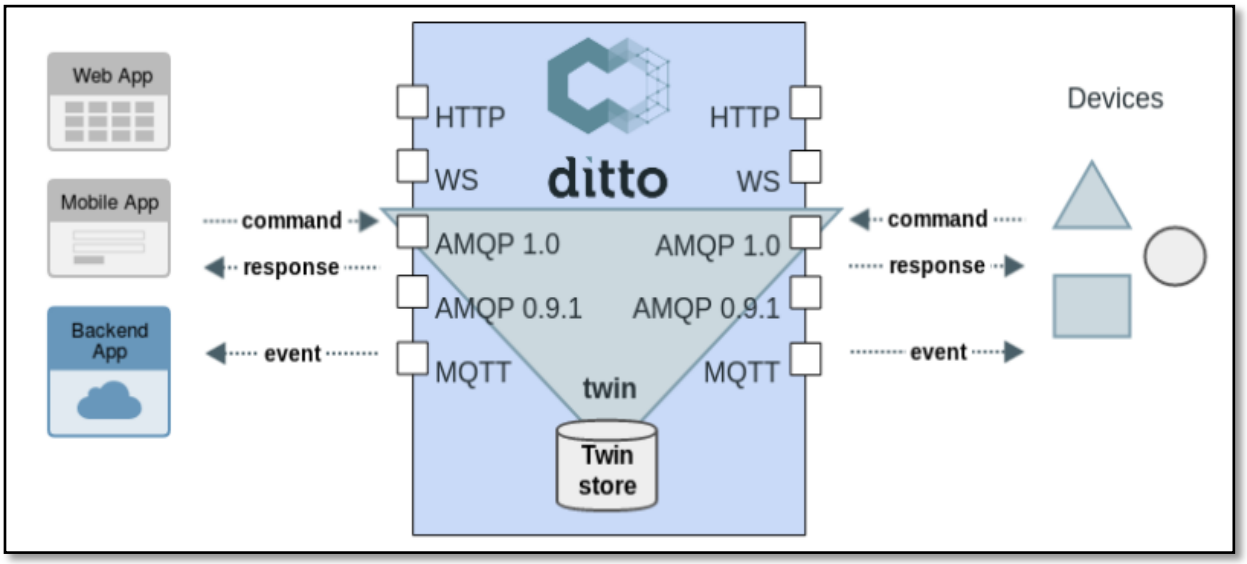



Figure 3.3: Ditto twin channel pattern [26].

**b) Live channel :**

In this case, Ditto functions as a router and enforces access control. For example an application might want to access the temperature of a sensor, but it wants to receive the live value, not the persistent one. Ditto then routes this message to the device, in this case, Ditto doesn't process the commands and emit the events. This is done by the applications and the devices. Ditto just relays the information.

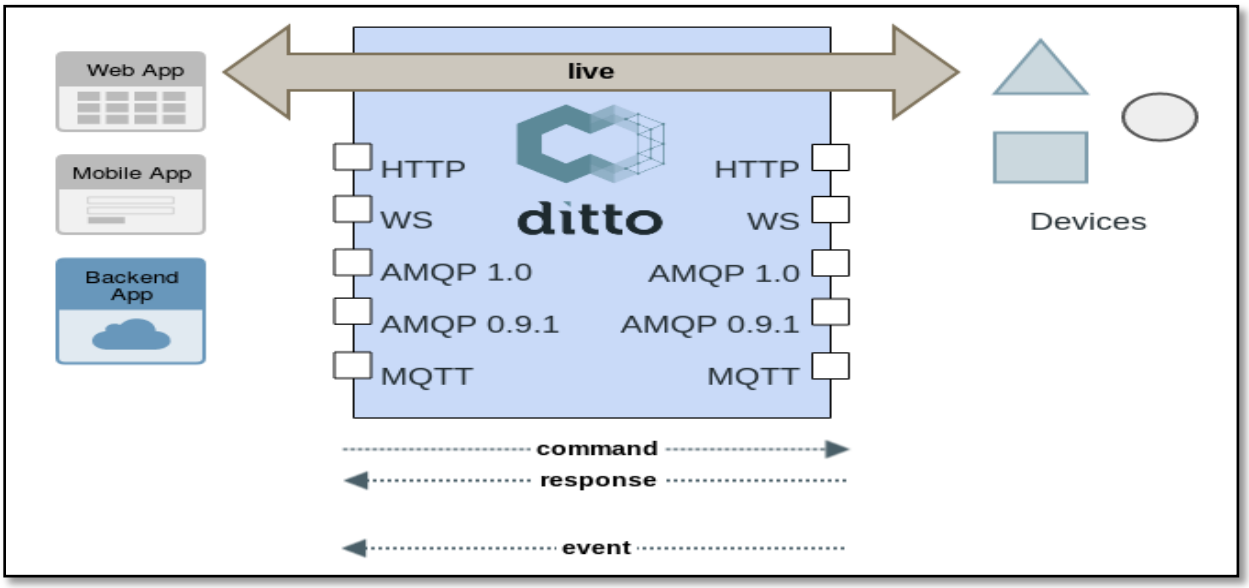



Figure 3.4: Ditto live channel pattern [26].

✓ In our water network application we have adopted the Twin channel as a solution. It's a persistent data structure where components (pumps, pipes, valve, etc.) are connected and store their last reported state. The application can read out this last reported state and can be notified about changes [28].

### 2.3.2. Things:

Things are very generic entities and are mostly used as a "descriptor" for multiple features belonging to this Thing. Exemples:

- **Physical device:** pump, pipe, reservoir, tank, Junction, valve.
- **Virtual device:** a room in a house, a virtual power plant spanning multiple power plants, or the weather information for a specific location collected by various sensors.
- **Transactional entity:** a tour of a vehicle (from start until stop), a series of measurements of a machine.
- **Master data entity**: a supplier of devices or a service provider for devices, an entity representing a city/region.

- **Thing ID:** Unique object identifier.
- **Policy ID:** Links to the ID of an existing policy that defines access control for the policy itself
- **Definition:** An object may contain a definition. The definition may also be used to search for objects and it is used to link an object to a corresponding model defining its capabilities/characteristics.
- **Attributes:** describe the object in more detail with any type. Attributes can also be used to search for objects. Static means that values do not change as frequently as values of property of the features [29].

### 2.3.3. Features:

A Feature is used to manage all data and functionality of a thing that can be clustered in an outlined technical context. For different contexts or aspects of a Thing, different Features can be used which are all belonging to the same Thing and do not exist without this Thing [25].

### 2.3.4. Property:

The list of properties is used to manage feature data. These characteristics can be categorized to manage the status, configuration, and any default information. A single JSON object is used to represent the entity attributes.[25]

### 2.4. Connection of water distribution network with digital twin

To make the connection between the real system and the virtual twin we have Node-Red as a programming tool for wiring together hardware devices

### 2.5. Anomalies detection

An anomaly is defined as a pattern that does not conform to expected normal behavior.

Anomaly detection is a critical topic in numerous industry sectors addressing issues such as fraud detection, security, safety in process engineering, manufacturing, infrastructure, distribution systems, and predictive maintenance [30].

✓ In our application we attempted to achieve the detection of water quality degradation and pipe obstruction.

✓

## 3. Use case diagram :

Use case diagrams describe the general functions of a system. These diagrams also identify the exchanges between the system and its actors.

Use cases and actors describe what the system does and how actors use it, but do not show how the system works internally.

Use case diagrams are useful in the following situations [31]:

- To model an enterprise before starting a project, so that all project participants can visualize the workers, customers, and activities.
- To record system requirements and inform people what the system needs to perform while gathering requirements.
- To determine the required classes during the analysis and design phases.
- To identify the tests to be performed for the system.

Model elements in use case diagrams [31]:

- **Use case** : A use case describes a function that a system runs to achieve the user's goal. A use case should return an observable result that is useful to the system user.
- **Actors**: An actor represents a role of a user who interacts with the system. The user can be a human user, an organization, a machine or another external system.
- **Subsystems**: In UML models, subsystems are a type of stereotyped component representing independent behavioral units in a system. Subsystems are used in class, component and use case diagrams to represent large components in the system.
- **Relations**: In UML, a relation is a connection between model elements. A UML relation is a type of model element that adds semantics to a model by defining the structure and behavior between model elements.

In our application we have three types of actors : "Supervisor", "Admin", and "Physic System".

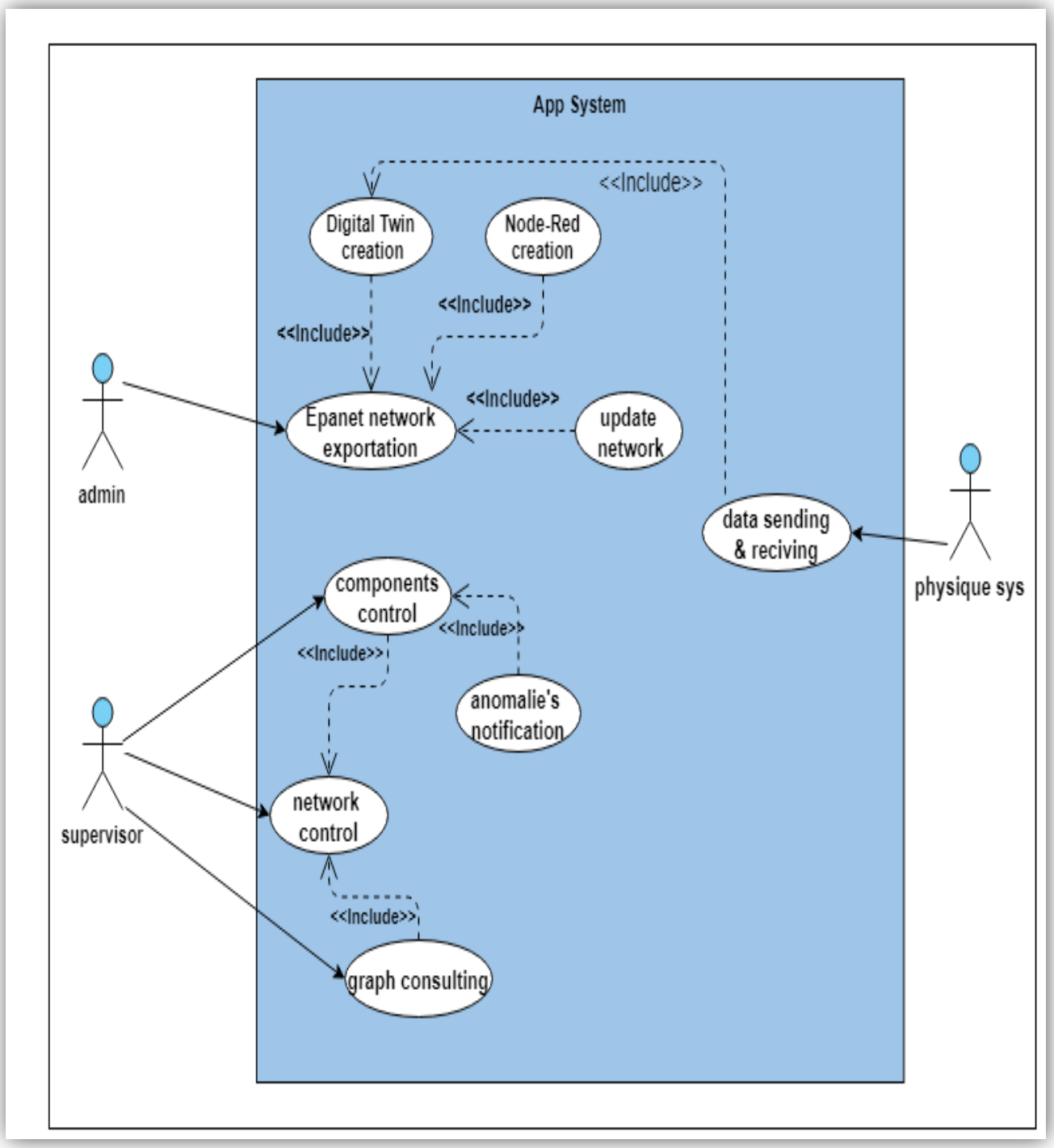



Figure 3.5 : Use case diagram

Scenario:

- The admin must first export the network from epanet in (.inp) format.
- Digital twin and node-red will be created.
- The admin can also update the network.
- The supervisor can control each of the network and its components and consult graphs.
- The supervisor can get the notification about anomalies if exist.

4. **Sequence diagram (dynamic model):**

A sequence diagram is an interaction diagram that details how operations are performed, including: what messages are sent and when they are sent. The sequence diagrams are organized according to time. The objects involved in the operation are listed from left to right depending on when they take part in the message sequence [32].

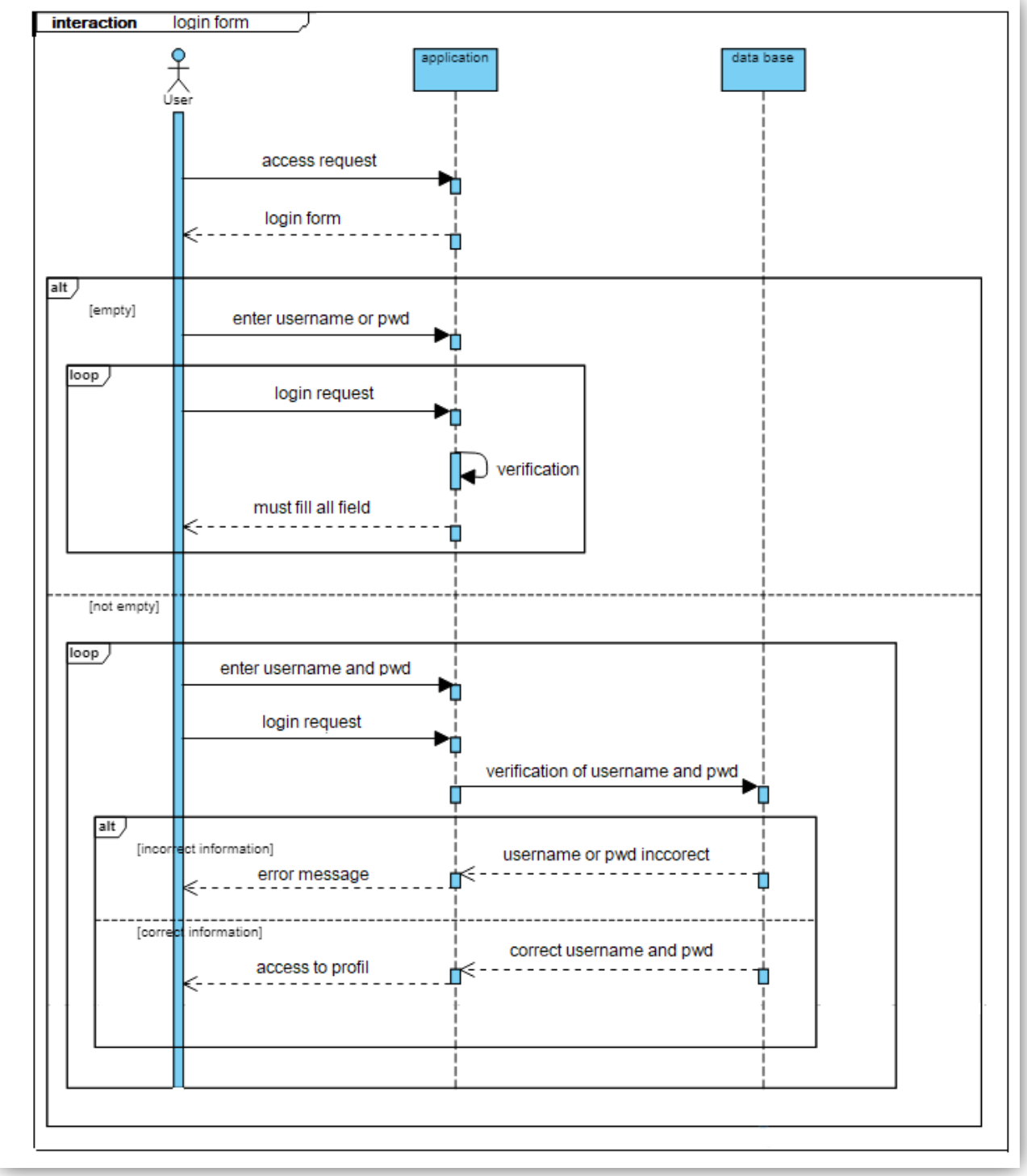



figure 3.6: Sequence diagram " login form".

Figure 3.6: explains how the user demand the access to application by entering username and password, if one of the fields is empty then an error message is send “must fill all fields”, else the application will verify if the username and the password are correct with those in the database. The user can access to the application only if the authentification is correct.

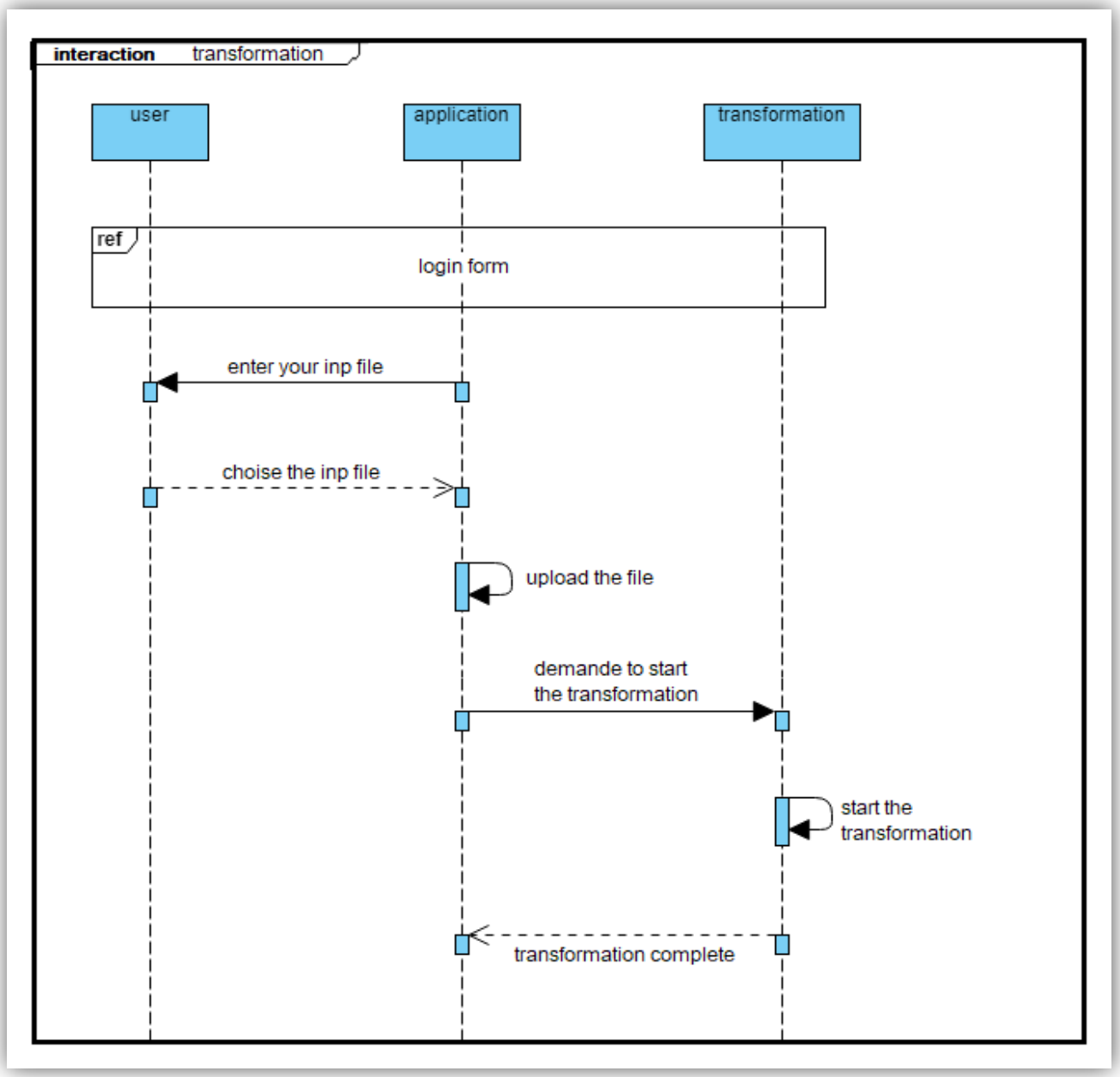



Figure 3.7: sequence diagram “ transformation”

Figure 3.7: Explains how the transformation is done, starting with entering the inp file then the application upload it and start the transformation step.

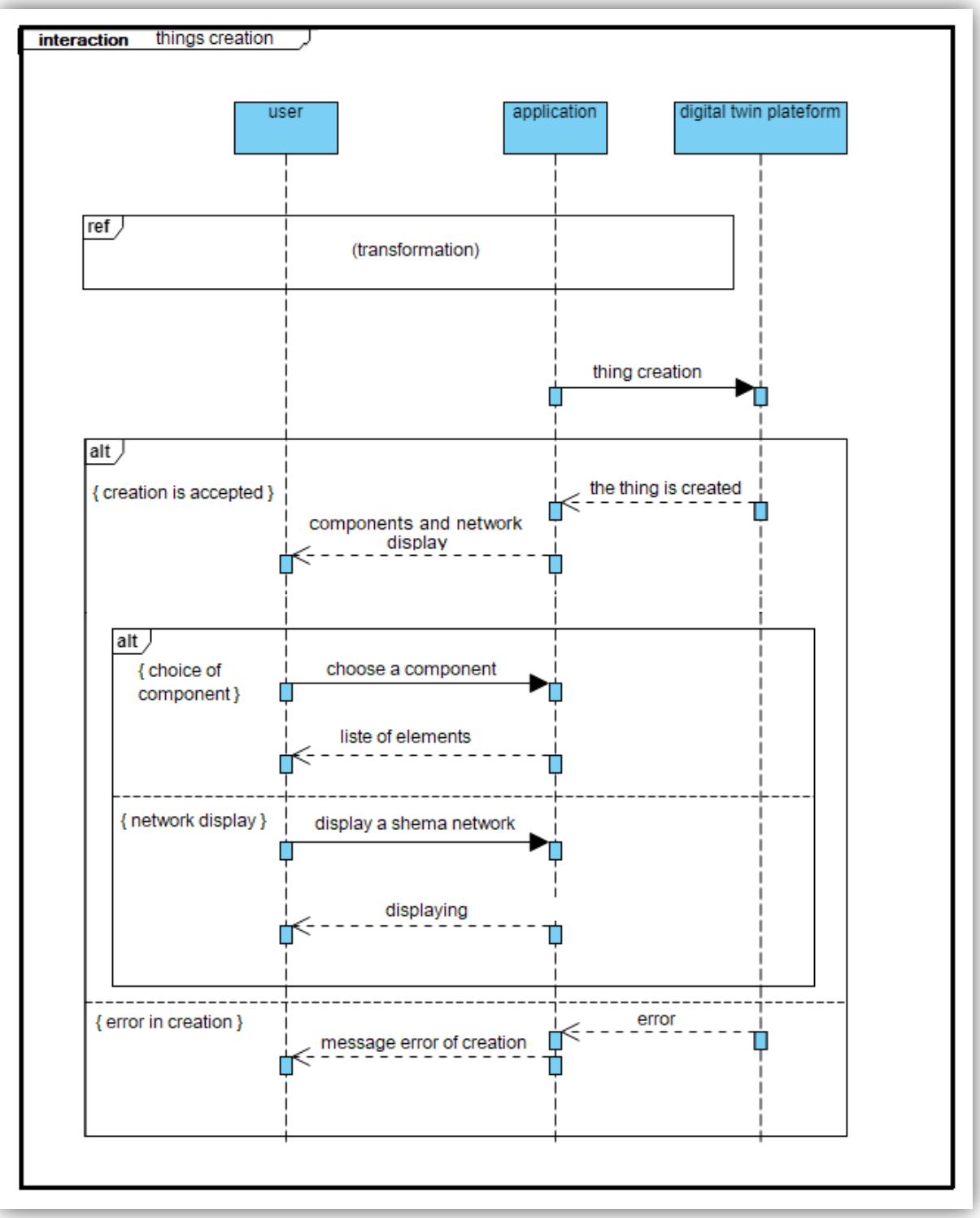



Figure 3.8: Sequence diagram “things creation”

Figure 3.8: Represent the things creation in Eclipse Ditto after the transformation is done.

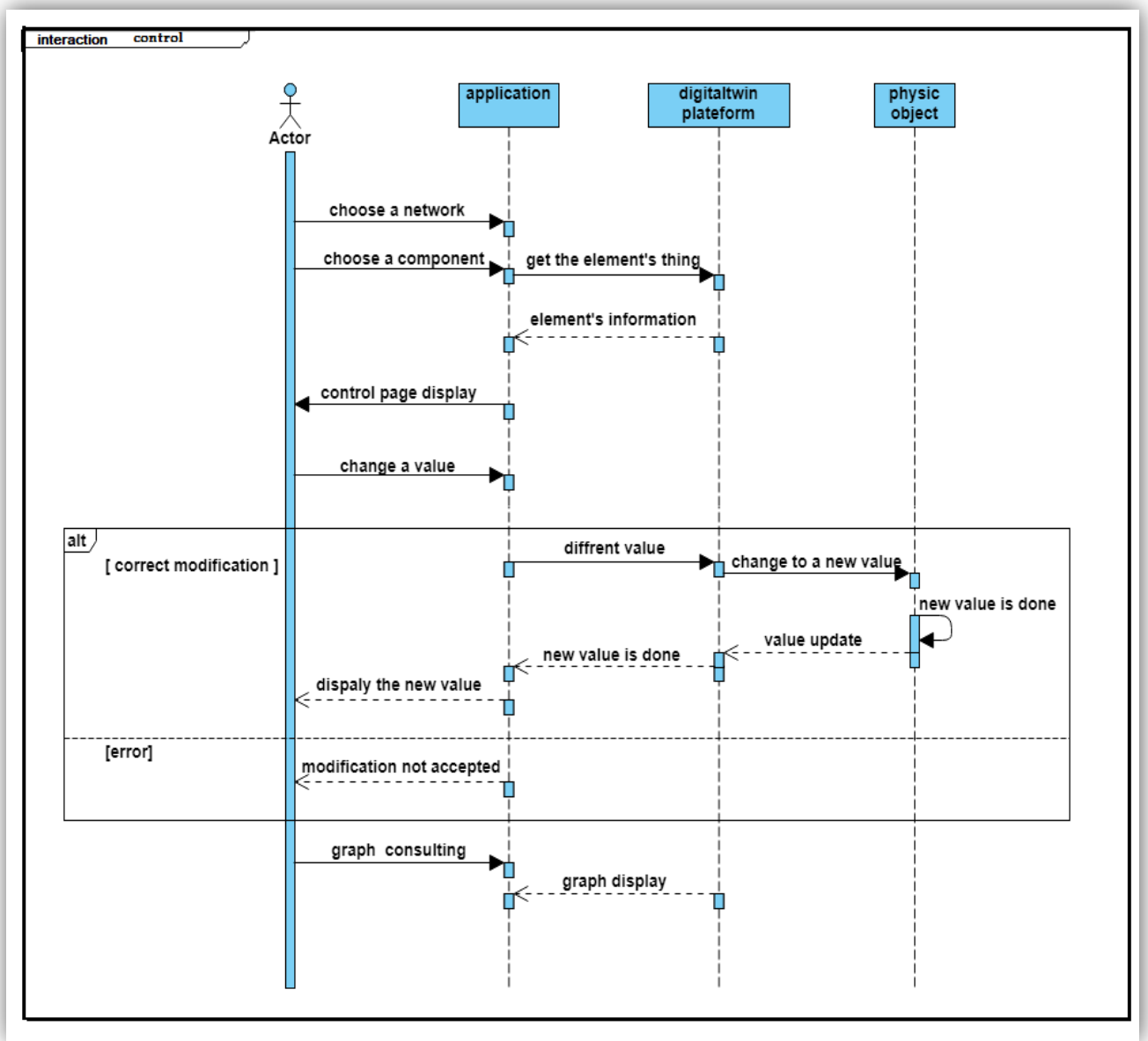



Figure 3.9: Sequence diagram “control”

The figure 3.9: Describes the he main steps to start the control phase of digital twin.

## 5. Conclusion :

This chapter talked about the project building steps, like the transformation to things and how the digital twin is generated from the initial network on Epanet.

The following chapter will present the implementation of this project.

# Chapter 4:
# Implementation

## 1. Introduction

We come to the last phase which is the implementation. It is the step that follows the conception. We were able to get a very clear idea of how our web application is going to be and how it would work using the different tools, and this is what led us to better understand its functionalities.

In this chapter we will mention all the stages from the water distribution network's exportation to the control and supervision of it, passing through various stages.

## 2. Water distribution network Exportation

Before coming to the application, the admin must first have the network into an (.inp) file format by exporting data from a network model

, this file will be obtained passing by these steps:

The user has the possibility to draw a new network or import an existed one to the epanet program, selecting file, then choose "export network" from the main menu, we must name it with the extension (.inp) then "save".

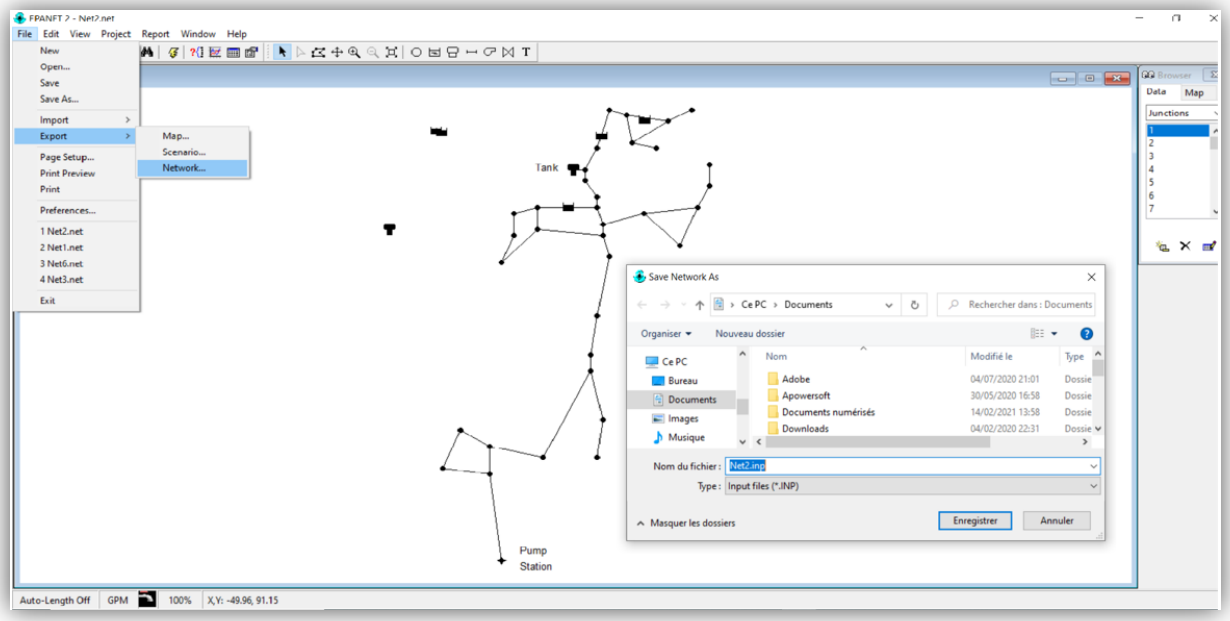



Figure 4.1 : Network exportation

## 3. Environment and development tools of our application

In order to be able to use our application properly we have opted for some programming languages that we used below:

### 3.1. HTML

HTML (Hypertext Markup Language) is the code that is used to structure a web page and its content. For example, content could be structured within a set of paragraphs, a list of bulleted points, or using images and data tables [33].

### 3.2. CSS

CSS is a language for specifying how documents are presented to users — how they are styled, laid out, etc. It can be used for very basic document text styling — for example changing the color and size of headings and links. It can be used to create layout — for example turning a single column of text into a layout with a main content area and a sidebar for related information. It can even be used for effects such as animation [34].

### 3.3. PHP

PHP (recursive acronym for PHP: Hypertext Preprocessor) is a widely-used open source general-purpose scripting language that is especially suited for web development and can be embedded into HTML [35].

### 3.4. JAVASCRIPT

JavaScript is a scripting or programming language that allows to implement complex features on web pages — every time a web page does more than just sit there and display static information— displaying timely content updates, interactive maps, animated 2D/3D graphics, scrolling video jukeboxes, etc. — It is the third layer of the layer cake of standard web technologies [36].

### 3.5. PYTHON

Python is an interpreted, object-oriented, high-level programming language with dynamic semantics. Its high-level built in data structures, combined with dynamic typing and dynamic binding, make it very attractive for Rapid Application Development, as well as for use as a scripting or glue language to connect existing components together. Python's simple, easy to learn syntax emphasizes readability and therefore reduces the cost of program maintenance. Python supports modules and packages, which encourages program modularity and code reuse. The Python interpreter and the

extensive standard library are available in source or binary form without charge for all major platforms [37].

### 4. Realisation

To load the file exported from Epanet program we made a web page coded with php and javascript ( the figure :4.2 represents the importation code ).

```
<form id="fileupload" action="../upload.php" method="POST" enctype="multipart/form-data" >
  <input type="file" id="myFile" name="files" multiple>
  <button type="submit" class="btn btn-primary" name = "upload" onclick="myFunction()">
  <span>Upload your network</span></button>
</form>
```

Figure 4.2 : Network importation code

This page is connected with the visualization page to give us the ability to access the network, from where the python tool was used to load it, using EPANETTOOLS which is a python package allowing the user to call all the functions of the toolbox in python scripts, and generate a json model for each component conforming to the Epanet model, here is an example for the junction data in the .inp and .json files.

```
[JUNCTIONS]
;ID                 Elev            Demand          Pattern
 6                  680             150                             ;
```

Figure 4.3: Junction data in (.inp) file

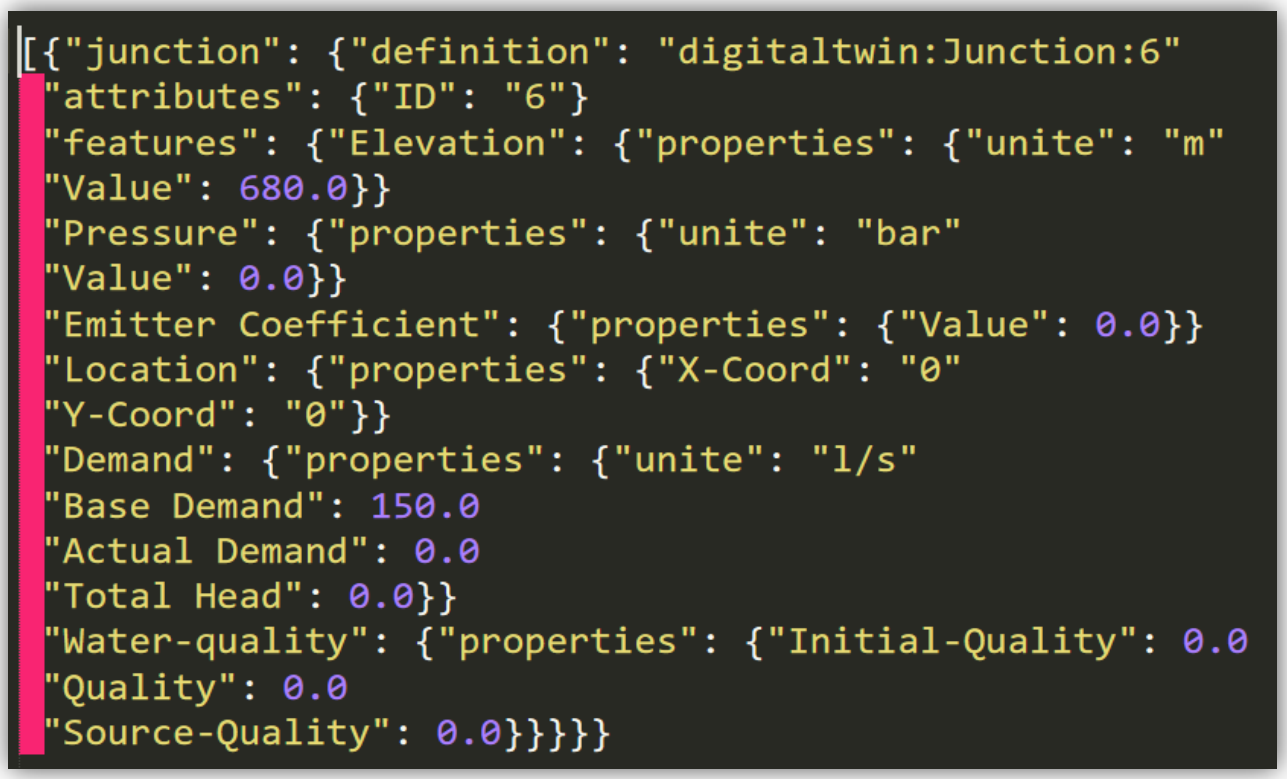



Figure 4.4 : Junction data in (.json) file

The figure 4.5 represents the same junction data transformed to thing in the digital twin platform.

```
[
  {
    "thingId": "first.junction:6",
    "policyId": "first.junction:6",
    "definition": "digitaltwin:Junction:6",
    "attributes": {
      "ID": "6"
    },
    "features": {
      "Demand": {
        "properties": {
          "unite": "l/s",
          "Base Demand": 150,
          "Actual Demand": 0,
          "Total Head": 0
        }
      },
      "Elevation": {
        "properties": {
          "unite": "m",
          "Value": 680
        }
      },
      "Water-quality": {
        "properties": {
          "Initial-Quality": 0,
          "Quality": 0,
          "Source-Quality": 0
        }
      },
      "Emitter Coefficient": {
        "properties": {
          "Value": 0
        }
      },
      "Pressure": {
        "properties": {
          "unite": "bar",
          "Value": 0
        }
      },
      "Location": {
        "properties": {
          "X-Coord": "0",
          "Y-Coord": "0"
        }
      }
    }
  }
]
```


Figure 4.5 : Junction data in the digital twin plateform

## 5. Supervision and control

The main role of our application is the water distribution network supervision and components control, so that we have passed by all the steps mentioned to reach our goal.

## 5.1. Things Creation in eclipse ditto

### 5.1.1. Eclipse ditto

Eclipse Ditto is a technology in the Iot implementing a software pattern called “digital twins” [38]. At the core of Ditto is a data model, called a ‘Thing’, that provides the representation of the physical device. The Ditto Thing is accessible through an API that allows digital twin domain experts to interact with the device. This API essentially creates a device-as-a-service for interaction with a digital twin [39].

### 5.1.2. Things creation

Once the transformation of (.inp) file to things is done, the things will be created in the digital twin platform (eclipse ditto).

The digital twin platform provides a capability (RESTAPI) to interact with the digital twin, this API is accessible through HTTP to be able to communicate with the network digital twin, on the other hand the digital twin platform provides several protocols as HTTP and Websocket, to communicate with the physical version that already contains the connected objects.

By using this digital twin we can control the network and have a real image in order to track a component in real time, and we can apply scenarios, while it guarantees us that access to the twin can only be done by the authorized party.

we create things using python, by putting (HTTP_RQUEST) to specify the ThingId codification.

## 5.2. Network visualization in real time

We gave the customer the option to see the network as a diagram depicted in an actual image where all components are easily examined for better control.

Providing all necessary data for simultaneous network monitoring and observation, as well as troubleshooting and keeping equipment working as effectively as possible to avoid breakdowns and downtime.

## 5.3. Real-time Network Control

HTTP was utilized to retrieve data from the digital twin platform and send it to our application. We can perform various operations on each network component. For example, we can display its information using the ‘GET’ method for data retrieval and the ‘PUT’ method for data modification. The display of information is dependent on the gender of the information; some information must be presented using a single value, while others must be presented using real-time graphs, for a clear and easy understanding.

One of the other operations is real-time notifications, which allow the user to monitor any anomalies identified in a network, such as leaks, pipe obstructions, and other issues, in order to address them at the appropriate time.

## 5.4. Simulation of the water distribution network in NODE-RED

### 5.4.1. Node-RED

Node-RED is a programming tool for wiring together hardware devices, APIs and online services in new and interesting ways. It provides a browser-based editor that makes it easy to wire together flows using the wide range of nodes in the palette that can be deployed to its runtime in a single-click [40].

### 5.4.2. Http request

An HTTP request is made by a client, to a named host, which is located on a server. The aim of the request is to access a resource on the server. To make the request, the client uses components of a URL (Uniform Resource Locator), which includes the information needed to access the resource [41].

### 5.4.3. Websocket

The WebSocket API is an advanced technology that makes it possible to open a two-way interactive communication session between the user's browser and a server. With this API, you can send messages to a server and receive event-driven responses without having to poll the server for a reply [42].

### 5.4.4. Network simulation

Physical assets, a virtual model, and the data and information connections that link virtual and actual environments should all be included in a digital twin model.

We used this simulation to collect information on the network component in real time during our work as part of the network simulation with Node-red. The connection between Node-red and the digital twin is formed via Http and Websocket at the same time. In Node-red, the following figure depicts a simulation of various network component information.

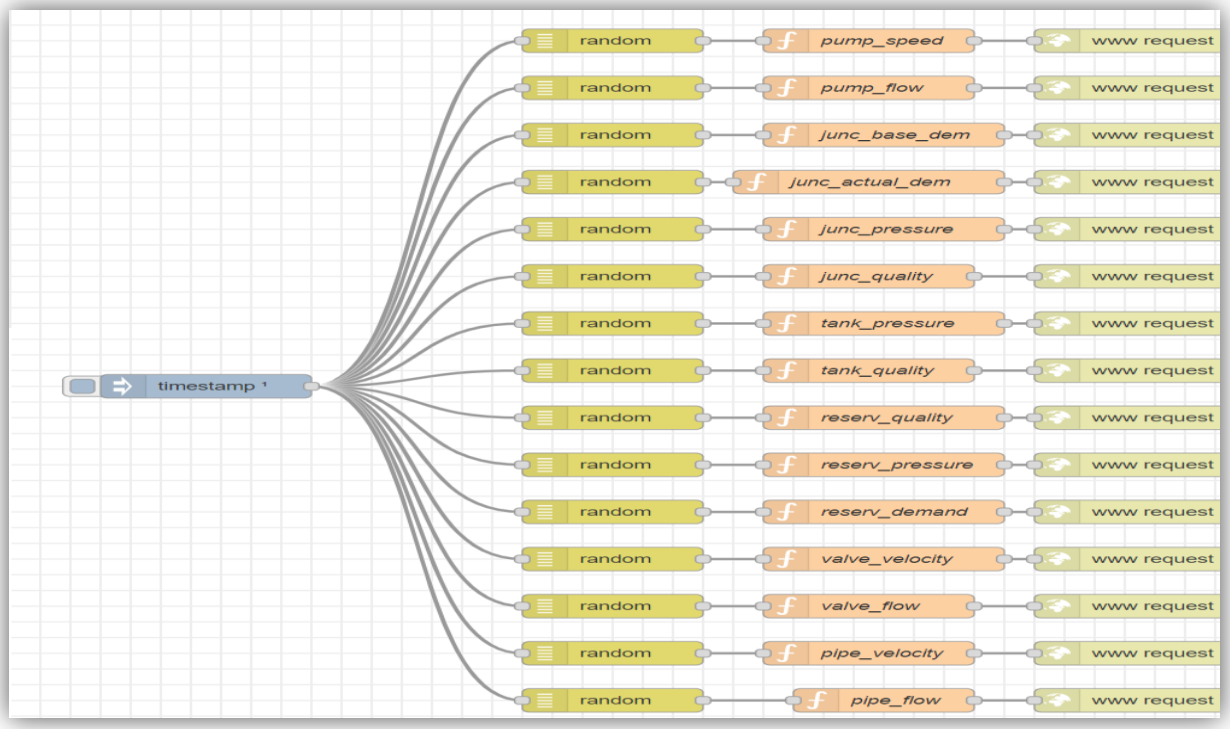



Figure 4.6 : Simulation of component information.

Figure 4.7 depicts a websocket simulation in nodered.

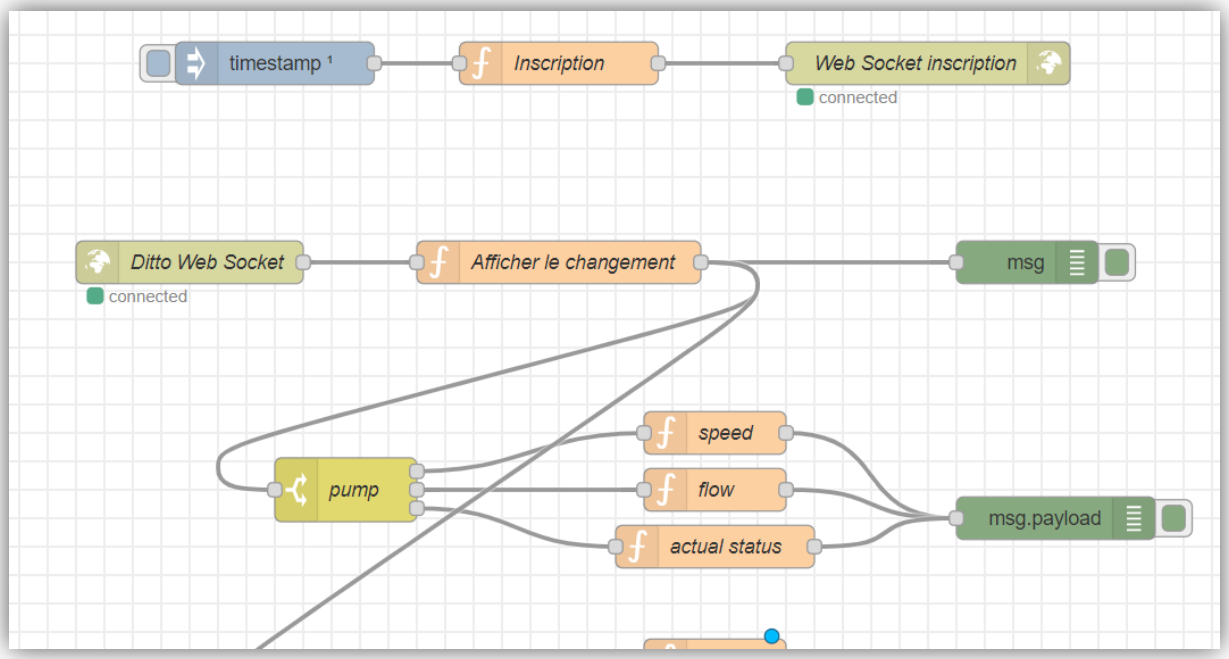



Figure 4.7: Websocket simulation in Node-red.

## 5.5. Application interfaces

### 5.5.1. Home page

As demonstrated in the following figures (4.8) to (4.11), the home page interface of our web application allows the user to: learn more about the application and get a sense of the application's content as well as network components, and have the option of contacting us.

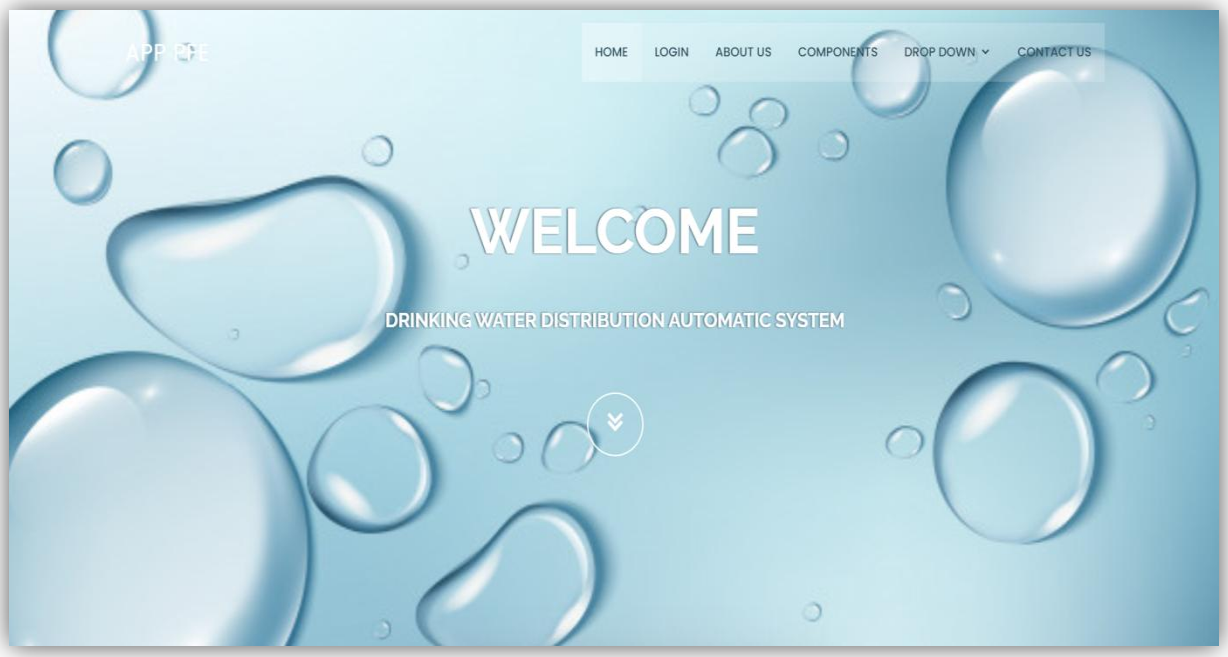



Figure 4.8: The first main home page.

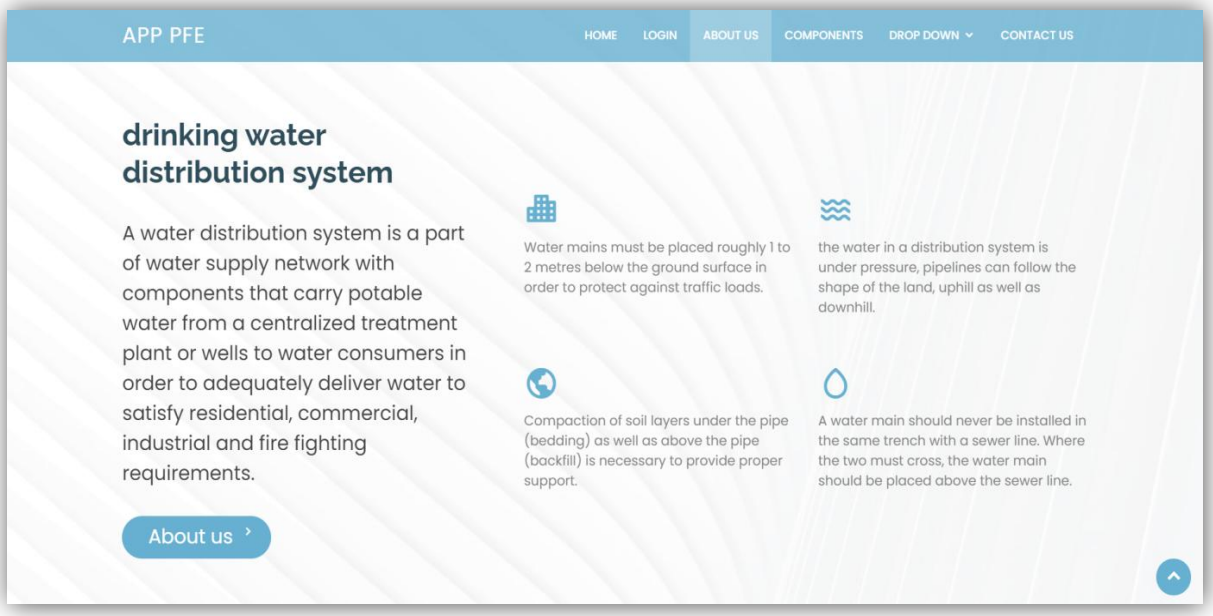



Figure 4.9: Part of about us in the home page.

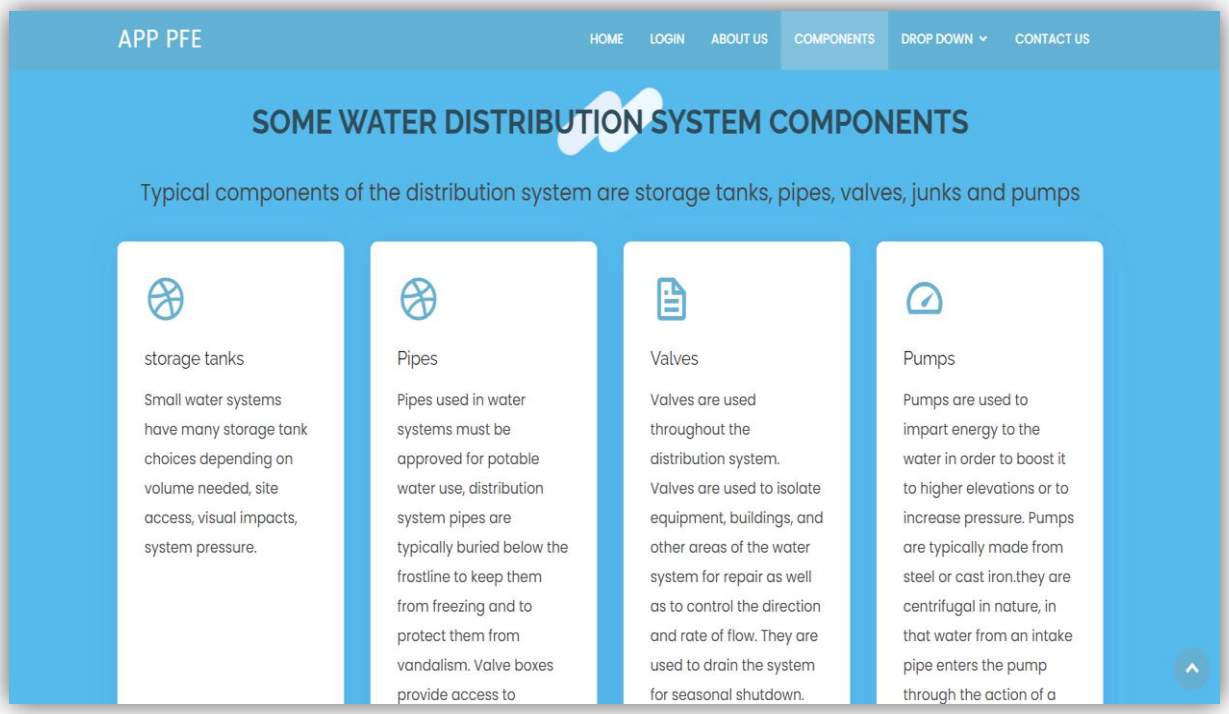



Figure 4.10: Some details about network components.

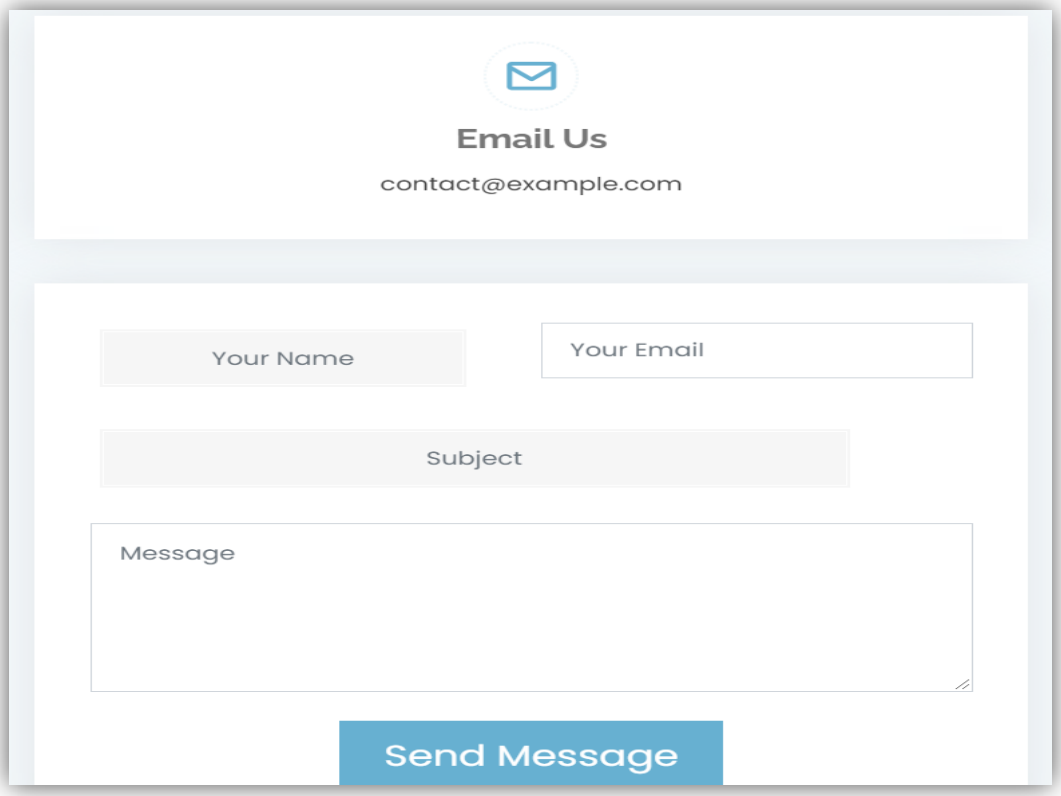



Figure 4.11: ‘Contact us’ in home page .

### 1.1.1. Network importation page

The admin is directed to a page that allows him to either download a new network or use a network of his previous ones, as seen in figure 4.12 which appears after successful authentication.

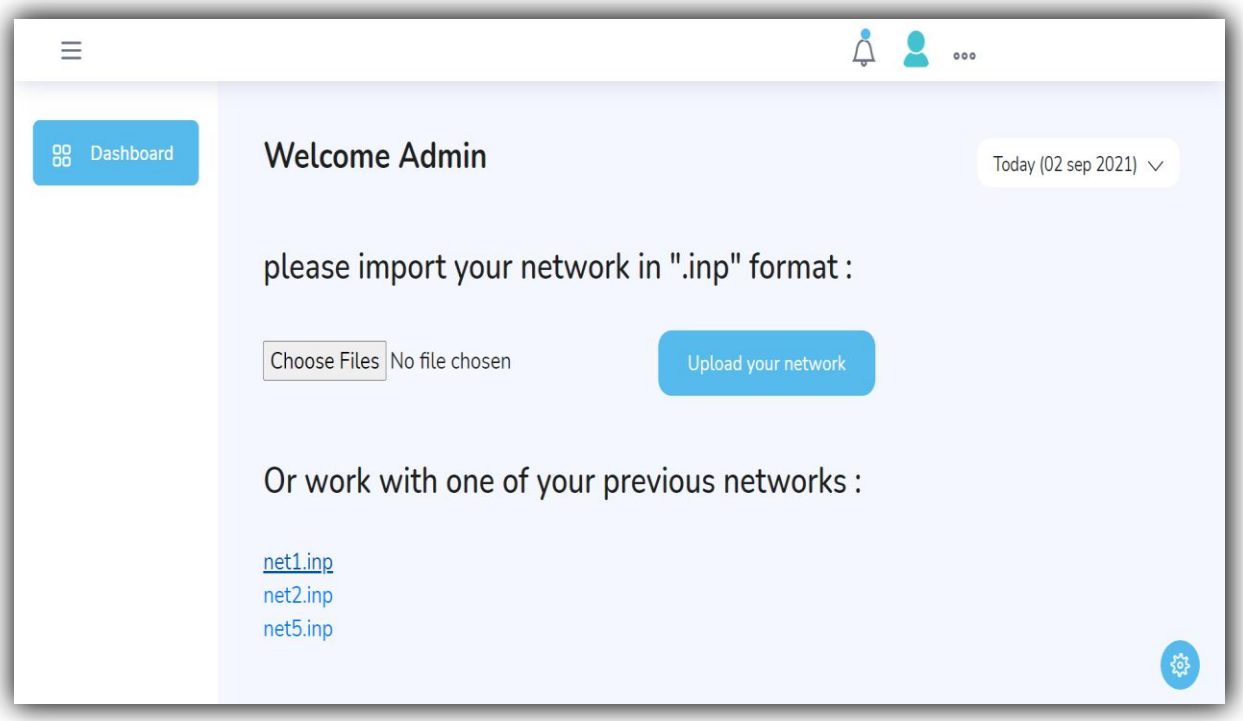



Figure 4.12: network uploading page.

### 1.1.2. Network visualization page

This is the network visualization and supervision interface, which appears after the choosed network uploaded (Figure 4.13).

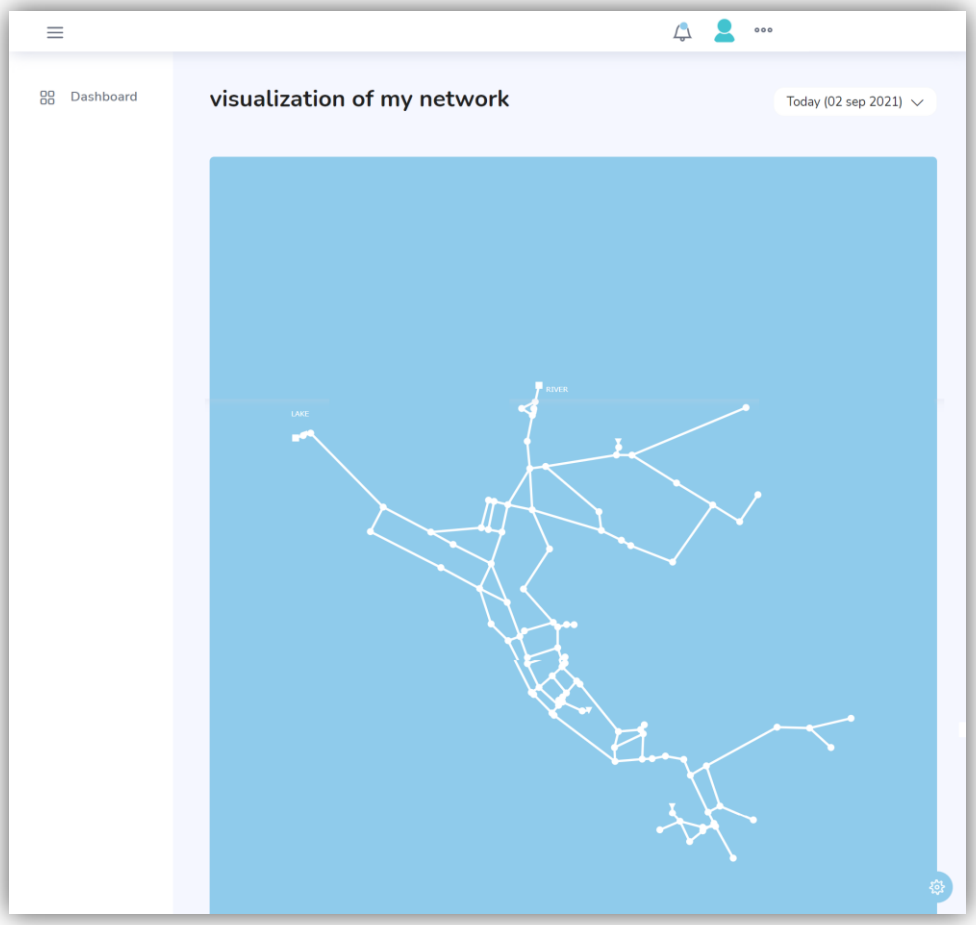



Figure 4.13: Network visualization page.

### 1.1.3. Component control page

Figure 4.14 shows how the admin can control one of these components by simply clicking on it in the network diagram.

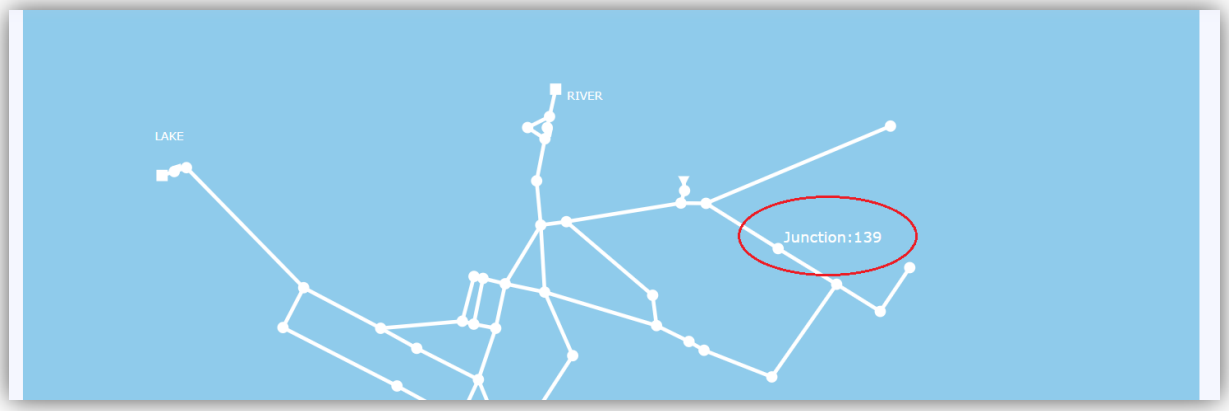



Figure 4.14: selecting component for control.

Selecting the component that we wish to manipulate or know more about (Figures 4.15 and 4.16)

Exemple 01 : Pump control

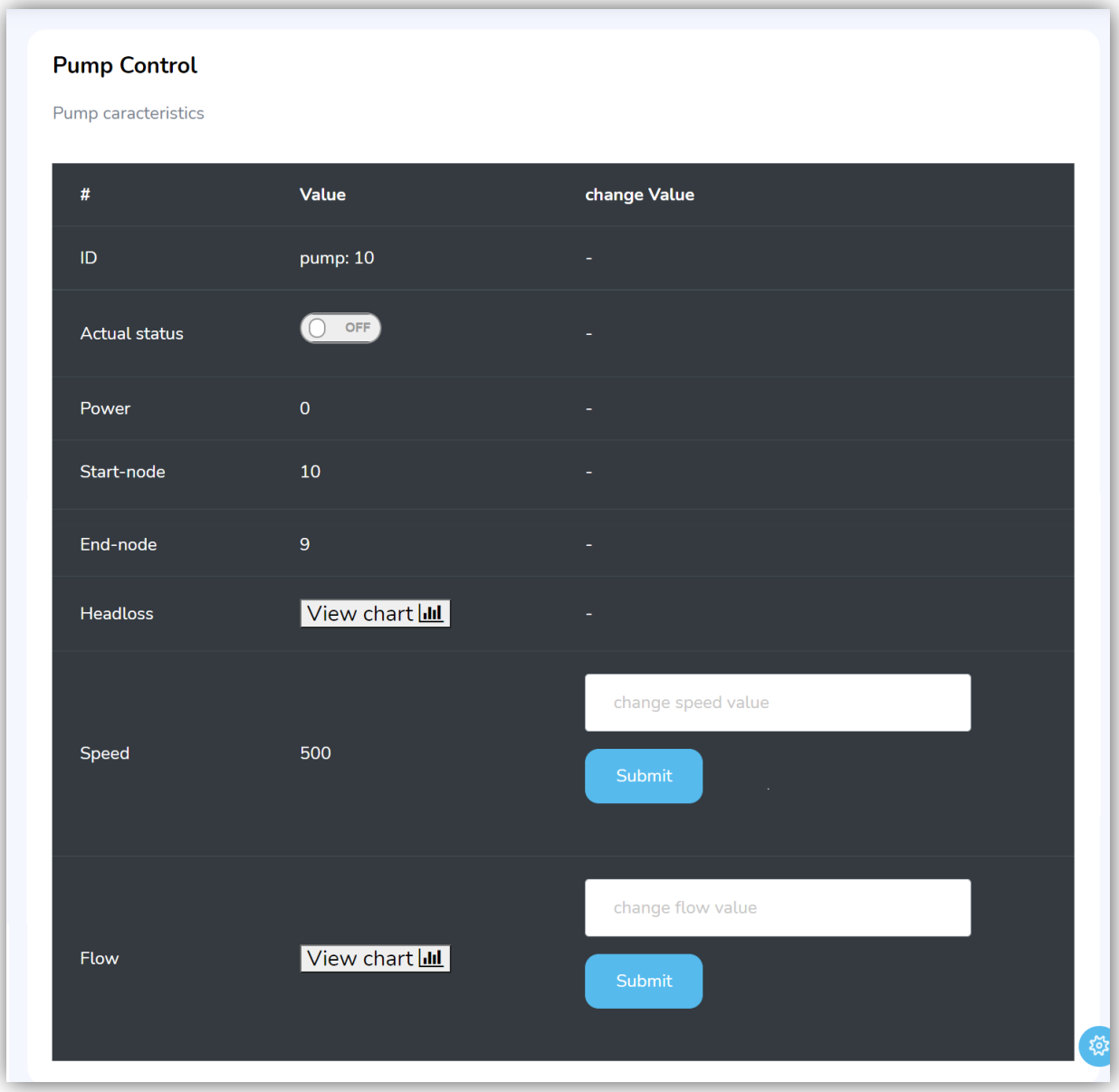



Figure 4.15: Pump control page.

Exemple 02 : Junction control

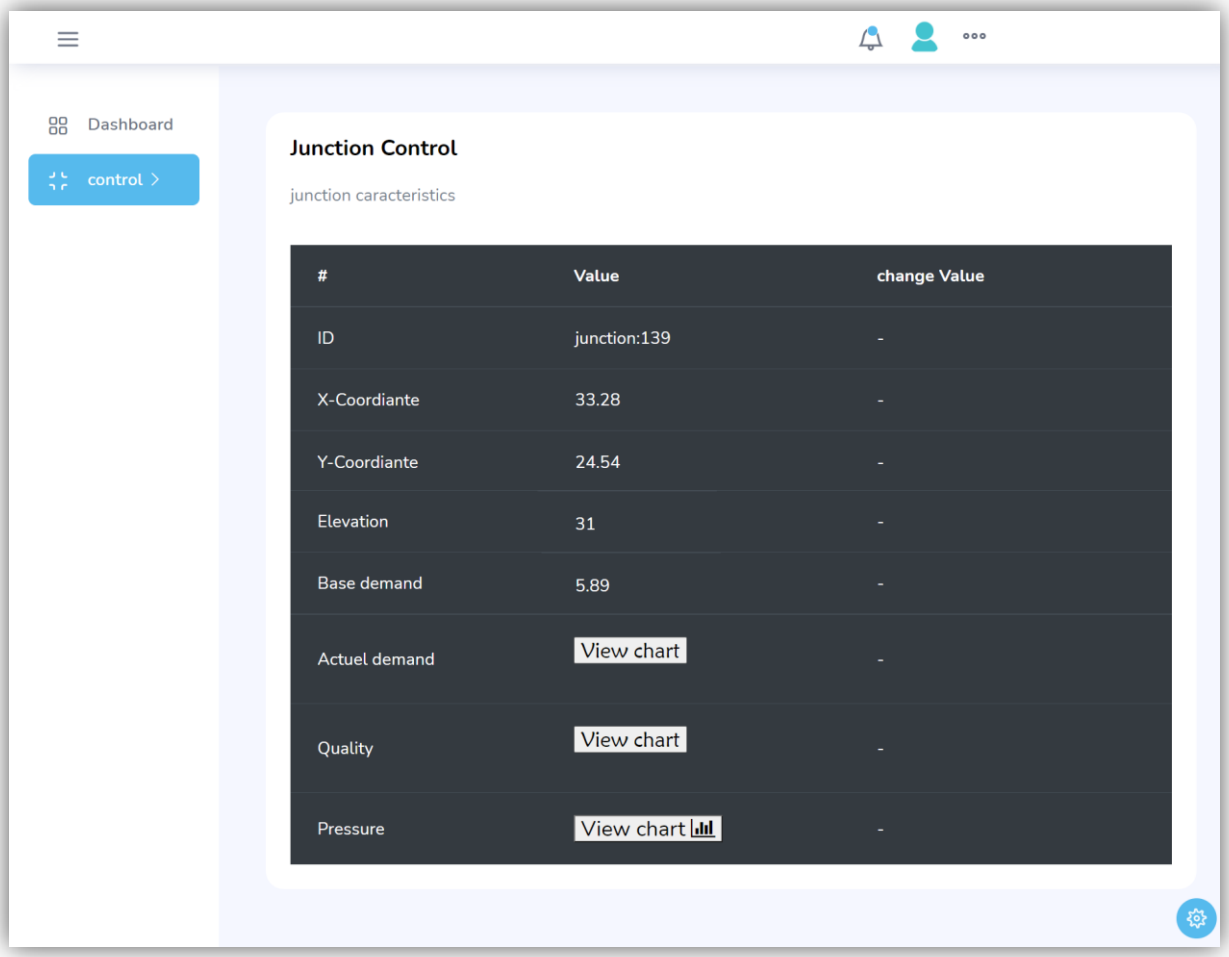



Figure 4.16: Junction control page.

### 1.1.4. Component's chart visualisation

When the user decides to consult the graphs in real time, these interfaces appear. When the user picks one of these pump charts, the program loads the graphs interface, as seen in the interface above.

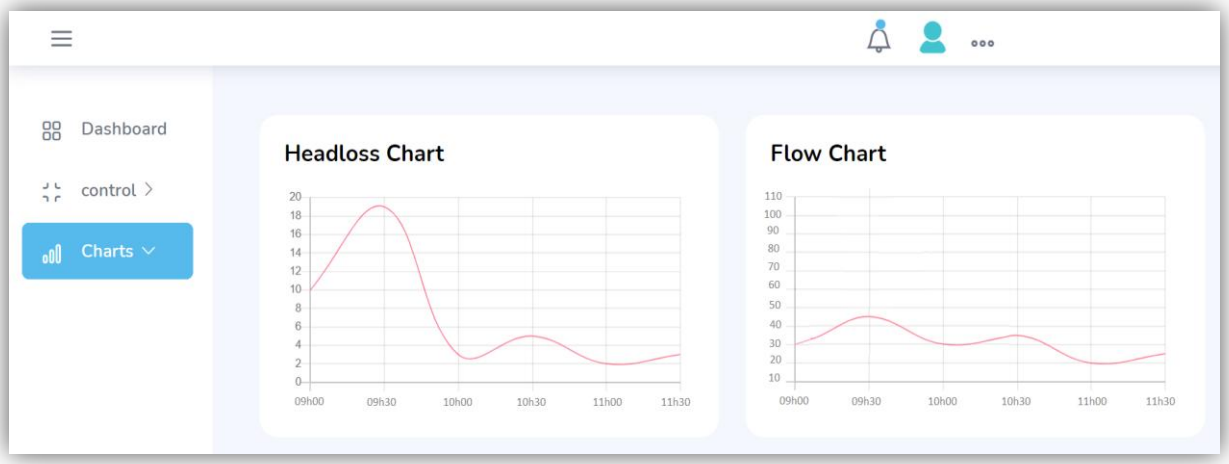



Figure 4.17 : Charts of a pump examination Page.

## 2. Conclusion

We have covered the phase of implementation and realization in this chapter, and we have thoroughly defined the system modeling as well as the many tools utilized. We finished this chapter with several interfaces to help visualize the project.

# General Conclusion

During the preparation of our end-of-semester project, we attempted to put the information we had gained during our university studies into practice in order to build an automatic approach for a digital twins developpement for a drinking water distribution system.

Throughout this thesis, we have examined and implemented the many steps of this project, beginning with the conception step and ending with the final product, which is a model for a smart water network. So for this ,we created a digital twin for a water distribution network in our application to learn about water system parameters that can't be monitored directly, such as water pressure and speed. The user may discover the location of possible abnormalities to prevent water loss by continuously updating the digital twins with measured operational data, leading in a more comprehensive system; enhancing network performance and efficiency assure network visualization.

This concept is for a system that can help in the administration of a water distribution network by allowing our application to manage all informations more efficiently.

Definitely, this experience has been beneficial and quite valuable to us, as it has helped us to gain understanding of new topics while also enriching our knowledge of programming tools. Finally, we hope that this effort is beneficial.

# Annex

✓ **Annex 01 :**

## Epanet

### 1. Background

EPANET is a widely used public domain tool for the analysis of water distribution systems. It has been the primary platform for the support of research in this area, a free multi-featured software package for modeling water distribution systems around the world, and as the technical basis for several highly successful commercial software packages. EPANET has helped to support critical investments in infrastructure improvements and operation at drinking water utilities worldwide.

EPANET was originally developed in 1993 by Dr. Lewis Rossman of the EPA Office of Research Development. Since then, EPA has continued to modify and distribute the software along with source code, documentation and a programmer's toolkit. Over the years, university researchers and private industry have developed modified versions of EPANET to meet their own needs. In 2016, the National Center for Infrastructure Modeling and Management (NCIMM) was awarded a USEPA grant with a charge to facilitate tech transfer of EPA's open source water infrastructure models including [33].

### 2. Definition

EPANET is a software application used throughout the world to model water distribution systems. It was developed as a tool for understanding the movement and fate of drinking water constituents within distribution systems, and can be used for many different types of applications in distribution systems analysis. Today, engineers and consultants use EPANET to design and size new water infrastructure, retrofit existing aging infrastructure, optimize operations of tanks and pumps, reduce energy usage, investigate water quality problems, and prepare for emergencies. It can also be used to model contamination threats and evaluate resilience to security threats or natural disasters [34].

### 3. Capabilities

With EPANET, users can perform extended-period simulation of the hydraulic and water quality behavior within pressurized pipe networks, which consist of pipes, nodes (junctions), pumps, valves, storage tanks, and reservoirs. It can be used to track the flow of water in each pipe, the pressure at each node, the height of the water in each tank, a chemical concentration, the age of the water, and source tracing throughout the network during a simulation period.

EPANET's user interface provides a visual network editor that simplifies the process of building pipe network models and editing their properties and data. Various data reporting and visualization tools are used to assist in interpreting the results of a network analysis, including color-coded network maps, data tables, energy usage, reaction, calibration, time series graphs, and profile and contour plots [34].

## 4. EPANET Usage Steps

The classic steps of using EPANET to model a water distribution are as follows [33]:

a. Draw a network representing the distribution system or import a basic network description saved in a text file.
b. Enter Network Element Properties.
c. Describe the system operation.
d. Select a set of simulation options.
e. Start a hydraulic simulation or quality analysis.
f. Visualize the results of a simulation.

# Bibliography

[1] https://www.waterrf.org/research/topics/intelligent-water-systems

[2] https://www.theengineeringprojects.com/2021/03/what-is-iot-internet-of-things-definition-meaning-devices-applications.html

[3] https://www.twi-global.com/technical-knowledge/faqs/what-is-digital-twin

[4] https://iot-analytics.com/internet-of-things-definition/

[5] https://www.cisco.com/web/solutions/trends/iot/overview.html consulté le 02/05/021

[6] https://data-flair.training/blogs/iot-architecture/

[7] https://medium.com/edureka/iot-applications-c62cd48b7363

[8] https://www.researchgate.net/figure/Application-domains-of-the-Internet-of-Things-image-courtesy-of-the-IoT-course-at_fig1_320125018

[9] https://www.redalkemi.com/blog/post/pros-cons-of-internet-of-things

[10] https://www.twi-global.com/technical-knowledge/faqs/what-is-digital-twin#HowDoesDigitalTwinTechnologyWork

[11] https://www.researchgate.net/figure/Enabling-technology-of-digital-twin_fig1_323397001

[12] https://www.idrica.com/blog/digital-twin-implementation-benefits-water-sector/

[13] https://slcontrols.com/what-is-digital-twin-technology-and-how-can-it-benefit-manufacturing/

[14] https://www.twi-global.com/technical-knowledge/faqs/what-is-digital-twin#Benefits

[15] http://sigesaqi.brgm.fr/Qu-est-ce-qu-un-reseau-d-eau-potable.html 04-04-2021

[16] https://h2ocoolers.com/news/different-types-of-water-sources/ 04-04-2021

[17] Muhammad Muhitur Rahman, Ataur Rahman, in Sustainable Construction Technologies, 2019

[18] https://www.nap.edu/read/11728/chapter/3#18 04-04-2021

[19] https://smartwaternetworks.com 4-5-2021

[20] https://www.indiamart.com/proddetail/smart-water-management-system-19011632933.html

[21] F.Martinez Alzamora . (2020) .Building and exploiting a Digital Twin for the management of drinking water distribution networks. Urban Water Journal

[22] https://www.wsp.com/en-GL/insights/digital-twin-your-essential-partner-in-water-management

[23] Hasan Habibul Latif. A Methodology for Developing Digital Twins in the Manufacturing Plant. A dissertation submitted to the Graduate Faculty of North Carolina. 2020

[24] https://www.epa.gov/water-research/epanet

[25] https://www.researchgate.net/figure/EPANET-Net-3-example-application-layout-with-two-EDSs_fig1_311528087

[26] https://www.twi-global.com/technical-knowledge/faqs/what-is-digital-twin

[27] https://www.eclipse.org/ditto/protocol-twinlive.html

[28] https://blog.bosch-si.com/developer/how-digital-twins-boost-development-in-the-iot/

[29] https://www.eclipse.org/ditto/protocol-specification-things.html#thing-representation

[30] Tashman, Z., Gorder, C., Parthasarathy, S., Nasr-Azadani, M. M., & Webre, R. (2020). Anomaly detection system for water networks in northern ethiopia using bayesian inference.
[31] https://www.ibm.com/docs/fr/rational-soft-arch/9.5?topic=diagrams-use-case
[32] http://docwiki.embarcadero.com/RADStudio/Sydney/fr/Définition_des_diagrammes_de_séquence_UML_1.5
[33] https://developer.mozilla.org/en US/docs/Learn/Getting_started_with_the_web/HTML_basics
[34] https://developer.mozilla.org/en-US/docs/Learn/CSS/First_steps/What_is_CSS
[35] https://www.php.net/manual/en/intro-whatis.php
[36] https://developer.mozilla.org/en-US/docs/Learn/JavaScript/First_steps/What_is_JavaScript
[37] https://www.python.org/doc/essays/blurb/
[38] https://artifacthub.io/packages/helm/eclipse-iot/ditto#:~:text=Eclipse%20Ditto%E2%84%A2%20is%20a,%2C%20EV%20charging%20stations%20etc).
[39] https://blog.bosch-si.com/developer/eclipse-ditto-1-0-a-framework-for-digital-twin-builders/
[40] https://nodered.org/
[41] https://www.ibm.com/docs/en/cics-ts/5.3?topic=protocol-http-requests
[42] https://developer.mozilla.org/en-US/docs/Web/API/WebSockets_API
[43] Murray, Regan et al. 2018. “Results from the Ewri Summit on the Future of Epanet.” 1st International WDSA / CCWI 2018 Joint Conference: 2016–19.
[44] https://www.epa.gov/water-research/epanet