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Norwegian University of
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Modeling Water Distribution Systems

Integration Between SCADA Systems and Hydraulic Network Simulation Models

Thomas Sjømoen Riis

Civil and Environmental Engineering

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Supervisor:	Sveinung Sægrov, IVM
Co-supervisor:	Rita Ugarelli, SINTEF Magnus Olsen, Oslo Kommune: Vann-og avløpsetaten

Norwegian University of Science and Technology
Department of Hydraulic and Environmental Engineering

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Problem description:

Oslo Water and Sewerage Works (VAV) wants to investigate options to optimize the efficiency of water used, and of the water demand strategies, to increase the reliability of the service provided. The motivation for this is that future projections for water demand in Oslo resulting from population growth are considered unacceptable. As such, the future goal of VAV is to maintain a stable and constant water production close to 100 mill. $m^3/year$ in the coming years regardless of the population growth. This can be achieved by reducing specific water consumption and by reducing water leakages in the network from about 30% to less than 20%. In order to achieve these goals, there is a need to promote new thinking and smart innovations for the water services .

Given the need to use sensitive data related to the network, an agreement for data sharing and on restrictions for the publication of the results has been signed between The Norwegian University of Science and Technology (NTNU) and VAV.

Specific tasks:

1. Build competence on the use of the hydraulic model WDNetXL in use at VAV.
2. Get an overview of the operational conditions for the selected pilot in Oslo and describe them as basis for the following work.
3. Get an overview of the SCADA system in use at VAV.
4. Define the data and format needed in the E^3-network model.
5. Retrieve data in the right format from the historian database.
6. Exemplify how the model can be refined with the use of actual data.

Responsible professor: Sveinung Saegrov, NTNU
Supervisor: Rita Ugarelli, SINTEF

Abstract

The water distribution system conveys water from the water treatment plant (WTP) to the user. A significant amount of the water is lost in the transit. The International Water Supply Association (IWSA) claims that the amount is typically 20-30% of the total water production depending on the overall state of the distribution system (Hunaidi et al., 2000). There is a great variation of the pipe material and the quality of construction of trenches for pipelines. Therefore, some distribution systems may lose as much as 50%. IWSA made a survey, which stated that the major cause of unaccounted for water loss is leakage.

VAV wants to investigate options to optimize the efficiency of water used, and of the water demand strategies, to increase the reliability of the service provided. The motivation for this is that future projections for water demand in Oslo resulting from population growth are considered unacceptable. As such, the future goal of VAV is to maintain a stable and constant water production close to 100 mill. $m^3/year$ in the coming years regardless of the population growth (Hovedplan vannforsyning 2015-2030, 2015). This can be achieved by reducing specific water consumption and by reducing water leakages in the network from about 30% to less than 20%. In order to achieve these goals, there is a need to promote new thinking and smart innovations for the water services.

This master thesis will specifically focus on analysing the specifications of a supervisory control and data aquisition (SCADA) system to be able to retrieve consistent data, in the right format, in order to calibrate hydraulic network simulation models (HNSMs). Among the main results from the thesis is the establishment of a link between a centralized SCADA database and a HNSM. Useful insights in data extraction will be provided together with an example of how the data can be used in model refinement. A pilot system of the water supply in Oslo, called the E^3-network, has been used as an example.

The HNSM used has been refined by implementing new demand patterns calculated from actual, retrieved data from a data historian. Also, the β-value of the model has been refined in order for the model to be more accurate.

Sammendrag

Et vanndistribusjonssystem transporterer vann fra vannbehandlingsanlegget til forbrukeren. En betydelig mengde vann går tapt i overføringen. IWSA hevder at 20-30% av den totale vannproduksjonen går tapt, avhengig av den generelle tilstanden på ledningene i distribusjonssystemet (Hunaidi et al., 2000). Det er nemlig store variasjoner i kvaliteten på rørmaterialet og på byggingen av grøfter for rørledninger. Derfor kan enkelte distribusjonssystemer miste så mye som 50%. IWSA har gjennomført en undersøkelse som konstaterer at den viktigste årsaken til vanntap i vanndistribusjonssystemer er lekkasje.

Oslo VAV ønsker å undersøke mulighetene for å optimalisere effektiviteten av vannforbruket, og forbruksstrategiene for vannforsyningen, for å øke påliteligheten av forsyningen slik den er i dag. Motivasjonen for dette er at fremtidige anslag for vannbehovet i Oslo som følge av befolkningsvekst anses som uakseptable. Som sådan har VAV satt et mål om å opprettholde en stabil og konstant vannproduksjon i nærheten av 100 mill. $m^3/år$ i de kommende årene uavhengig av befolkningsveksten (Hovedplan vannforsyning 2015-2030, 2015). Dette kan oppnås ved å redusere spesifikt vannforbruk og ved å redusere vannlekkasjer i nettverket fra ca 30% til mindre enn 20%. For å oppnå disse målene er det behov for å fremme nye tanker og smarte innovasjoner i vannsektoren.

Denne masteroppgaven vil fokusere på å analysere et SCADA system for å kunne hente ut gode data, i riktig format, som kan brukes til å kalibrere hydrauliske netverksmodeller. Blant de viktigste resultatene fra avhandlingen er etableringen av en kobling mellom en sentralisert SCADA database og en hydraulisk nettverksmodell. Oppgaven gir innsikt i datauthenting, og presenterer et eksempel på hvordan dataene fra et SCADA system kan brukes for å gjøre hydrauliske modeller mer pålitelige. Et pilotsystem i Oslo, kalt E^3-nettverket, har blitt brukt som et eksempel. Det overordnede målet er å hjelpe VAV med å nå sitt mål om å redusere vannlekkasjeandelen i Oslo.

Modellen som har blitt brukt har blitt forbedret ved at nye forbruksmønstre er implementert. Disse er kalkulert ut i fra faktiske data, som er hentet fra databasen til VAV. β-verdien er også forbedret, noe som har gjort modellen mer nøyaktig.

Preface

This thesis is written at The Norwegian University of Science and Technology as part of the master course "TVM4905 VA-teknikk". It is written over a period of one semester, and totaled 30 credits. The thesis examines the fields of online monitoring systems, e.g. SCADA systems, and HNSMs, and establishes a link between the two.

My interest within the specialty field of leakage management developed during a summer internship at the department of leakage and technical service within the Oslo Water and Sewerage Works in 2013. Through this internship I realized how complex and overwhelming the challenges that water utilities around the world face regarding water loss in water distribution networks. Therefore, it was very rewarding and interesting to develop a master thesis within this field. The master thesis has been written in cooperation with both SINTEF and VAV. This thesis serves as supporting work for an ongoing SINTEF project, called E^3.

The underlying idea of using leakage management, and especially dynamic pressure management, as a subject for both the project and the thesis was first brought to me by the leader of the Department of Water Distribution in VAV, Lars Wermskog. My supervisor, Rita Ugarelli, then further developed the idea to what it has become today.

Working with sensitive data has been a challenge. The new guidelines, laws, and regulations in relation to increased cyber security for the water sector have created major complexity in handling data to and from VAV. The agency are constantly working with adjusting their practices for meeting the new requirements. As an unauthorized user, this meant I had to apply for permissions for every system I needed access to. Another consequence is that I have had to follow strict restrictions for what I was allowed to include in the thesis, and what not.

Regardless of the challenges I've faced, it is a great pleasure to deliver a final product within the limits set by my supervisor during the semester.

Oslo, 15.juni 2016

Thomas Riis

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Finally, I would like to thank my friends and family for their support.

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List of Acronyms

ANOVA analysis of variance.

COTS commercial off-the-shelf.

DDA demand driven analysis.
DDM demand-driven model.
DMA district metered area.

EPS extended period simulation.

GA genetic algorithm.

HMI human-machine interface.
HNSM hydraulic network simulation model.

IAM infrastructure asset management.
ICT information and communication technology.
IED intelligent electronic device.
IO input/output.
IP internet protocol.
IVS isolation valve system.
IWSA The International Water Supply Association.

LAN local area network.

MNF minimum night flow.

MOGA multi-objective optimization algorithm.

MTU master terminal unit.

NTNU The Norwegian University of Science and Technology.

PC personal computer.

PCV pressure control valve.

PDA pressure driven analysis.

PDM pressure-driven model.

PLC programmable logic controller.

PRV pressure reduction valve.

RFF regionalt forskningsfond.

RRTC remote real time control.

RTU remote terminal unit.

SCADA supervisory control and data aquisition.

SSS steady state simulation.

TCP transmission control protocol.

VAV Oslo Water and Sewerage Works.

VSP variable speed pumps.

WAN wide area network.

WDN water distribution network.

WDS water distribution system.

WTP water treatment plant.

Chapter 1
Introduction

1.1 Background

WDNs require innovational technical solutions to meet the growing water demand. One of the biggest problems that are related to water network systems is compounded by the age of the infrastructure. The rate of renewing the pipes has been, and still is, too low. One third of the water utilities worldwide have 20% or more of their pipelines nearing the end of their useful life (Candelieri et al., 2013). This indicates that there is a great demand for renewal of the pipes. This also means that there are a lot of pipes that have reached their life expectancy before they are renewed and are therefore at risk of fracture and fatigue.

The water distribution system conveys water from the WTP to the user. A significant amount of the water is lost in this transit. IWSA claims that the amount is typically 20-30% of the total water production depending on the overall state of the distribution system (Hunaidi et al., 2000).There is a great variation of the pipe material and the quality of construction of trenches for pipelines. Therefore, some distribution systems may lose as much as 50%. IWSA made a survey, which stated that the major cause of unaccounted for water loss is leakage.

The most frequently used definition of leakage is: the amount of water which escapes from the pipe network by means other than through a controlled action (Ofwat, 2008). Leaks result in both primary and secondary economic loss. The value of the loss is related to primary causes, such as the cost of raw water, its treatment and transportation, as well as secondary causes in the form of damage to the pipe network, and to foundations of roads and buildings. There are also health risks related to leaks. One of the main reasons is that bacteria from the surrounding soil can infect the pipes when the pressure drops inside the pipe.

One of the approaches to the combined problem of increasing water demand and rehabilitation of the network is to minimize water leakage with improved leakage management. Leakage management can be divided into four components: quantifying water loss, leakage monitoring, leak localization and pinpointing, and network pressure and asset management (Mutikanga et al., 2012).

Measurements of the water balance can sometimes be used to verify an existing leak. A source such as water mains would for instance be identifiable using this method. This makes it an effective tool for systematic accounting of water supply and consumption. However, the method will not work if the source makes up a small part of the water balance or when the data have high uncertainty.

Leakage monitoring involves measuring flows and pressures continuously into discrete zones or DMAs. The goal of such a system is to determine the leakage flow, which is the excess flow beyond the legitimate customer usage at the time of minimum night flow (MNF). During this time, customer usage is usually at a minimum, network pressures are high, and the leakage percentage is at a maximum of the total flow. MNF is generally considered to occur between 02:00 and 04:00. One of the main challenges with leakage monitoring is that pipes supplying large DMAs are less sensitive to changes in demand. Therefore, it is more difficult to detect any sudden burst or background leakage that is the same order of magnitude as domestic consumption (Jankovic-Nisic et al., 2004).

Leak localization is an activity that identifies and prioritizes the areas of leakage in a pipe network to make pinpointing of leaks easier, whereas leak-pinpointing methods refers to pinpointing the exact position of a leak. The most common leak localization methods are acoustic logging, ground penetrating radars, and thermography. Acoustic devices are the most commonly equipment that is being used in leak pinpointing. Such devices listen for the sound induced by water as it escapes from pipes under pressure. These include leak noise correlators and other listening devices, such as hydrophones and ground microphones. The operation of listening devices is usually straightforward, but their effectiveness depends on the experience of the user (Hunaidi et al., 2000; Puust et al., 2010). However, recent advancements in technology and communication facilities have led to modern acoustic equipment. Sensors equipped with multi parameter measurements (flow, pressure, and noise) can be connected to the pipe, which is more effective and less dependent on user experience (Mutikanga et al., 2012).

Asset management combines engineering and mathematical analyses with sound business practice and economic theory in order to make the best decisions about the management of an organization's physical assets throughout their entire life cycle (Ugarelli et al., 2010). Pressure management is used to enhance reduction of leaks and unaccounted for water loss by means of dynamic pressure regulation between urban zones in a water network. Asset and pressure management offer a base for more reliable, efficient operation of water piping systems and major financial benefits, both important to utility management in urban settings. They offer a means for increased productivity, help reduce failure events and lead to minimized potable water (Ehrenreich and Arlosoroff, 2007). It is also argued that these are the only tools that can reduce background leakage (unreported and undetected leaks) once pipes have been buried in the ground (Mutikanga et al., 2012).

1.2 Objective and approach

VAV wants to investigate options to optimize the efficiency of water used, and of the water demand strategies, to increase the reliability of the service provided. The motivation for this is that future projections for water demand in Oslo resulting from population growth are considered unacceptable. As such, the future goal of VAV is to maintain a stable and constant water production close to 100 mill. $m^3/year$ in the coming years regardless of the population growth. This can be achieved by reducing specific water consumption and by reducing water leakages in the network from about 30% to less than 20%. In order to achieve these goals, there is a need to promote new thinking and smart innovations for the water services .

This master thesis will specifically focus on analysing the specifications of a SCADA system to be able to retrieve consistent data, in the right format, in order to calibrate HNSMs. Among the main results from the thesis is the establishment of a link between a centralized SCADA database and a HNSM (Figure 1.1). Useful insights in data extraction will be provided together with an example of how the data can be used in model refinement. A pilot system of the water supply in Oslo, called the E^3-network, has been used as an example. The overall goal is to aid VAV reach their goal of reducing water leakages in their WDN.

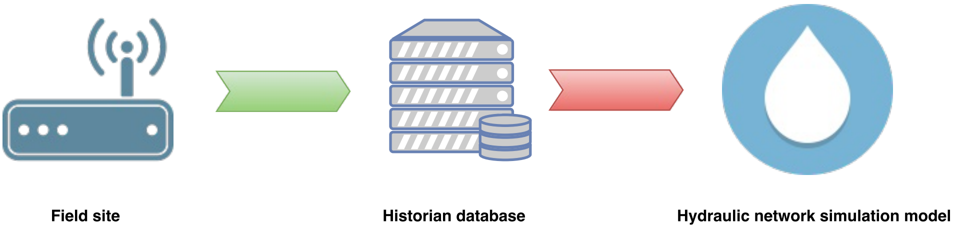

Figure 1.1: One of the objectives of the thesis is to establish an efficient link between a centralized SCADA database and a HNSM.

The specific tasks of the thesis includes:

1. Build competence on the use of the hydraulic model WDNetXL in use at VAV.

2. Get an overview of the operational conditions for the selected pilot in Oslo and describe them as basis for the following work.
3. Get an overview of the SCADA system in use at VAV.
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Given the need to use sensitive data related to the network, an agreement for data sharing and on restrictions for the publication of the results has been signed between NTNU and VAV.

Adjunct Professor Rita Ugarelli (Deparment of Hydraulic and Environmental Engineering, NTNU) will be the main supervisor for this master thesis, assisted by Professor Sveinung Saegrov. Magnus Olsen will be the contact person at VAV.

1.3 Research contributions

E^3WDM is a Regionalt forskningsfond (RFF) project which goal is to promote new thinking and smart innovations in the water service. The ultimate goal of the project includes the use of information and communication technology (ICT) solutions to adapt and upgrade existing water infrastructure of Oslo to support a more efficient, effective and economic water demand management in the growing city. Direct benefits are expected to come from the reduction of inefficiencies and their impact. Reduction of the water demand component related to background leakages is of primary importance since they represent loss of revenue and are responsible of extra pumping, treatment, and operational costs.

The overall goal of the project is to ensure *efficient*, *effective*, and *economic* water demand management in the growing city of Oslo. There are established 7 secondary objectives to help achieve the overall goal. The first of these objectives is defined as follows:

1. Develop a smart water distribution network model that integrates WDNetXL, Remote real time controls (RRTCs), and ICTs tailored to the specific challenges of the Oslo network.

The thesis will provide support for the achievement of this objective, as the main focus is to integrate an ICT SCADA system with hydraulic models. More specifically, the thesis contributes to the work of work package 2 (WP2), which focuses on the E^3 pilot network. Among the main results expected in this WP is the creation of a calibrated HNSM of the pilot network in WDNetXL. Th model will be subject to continuous development and refinement until the end of the pilot phase, and the thesis should be seen as a step towards achieving this.

There are three main contributions from this thesis:

1. An analysis of the specifications of a specific SCADA system in order to retrieve consistent data in the right format. The data is formatted for calibration of hydraulic models.
2. A relatively simple method for retrieving data from the central SCADA database (historian) is presented, along with comprehensive theory regarding the data quality. An example of how the data can be formatted and used in WDNetXL is also included.
3. Real-world data is retrieved to help refine the first iteration of the model. The calibration will make the model more representative, and make the simulations more accurate.

1.4 Structure of the thesis

There are two minor chapters included in the thesis: Introduction (chapter 1) and Concluding remarks (chapter 9). The rest of the thesis is laid out as follows:

- Chapter 2 introduces the concept of critical infrastructure as defined by The Norwegian Government and explains the restrictions related to the work of the thesis.
- Chapter 3 presents the fundamentals of online monitoring with respect to water distribution systems (WDSs). The chapter gives an in-depth explanation of the logic behind SCADA systems, and presents the Aquis model, which is used by VAV.
- Chapter 4 presents the SCADA system in use at VAV and provides useful insights in how to retrieve data from a historian database.
- Chapter 5 goes into detail about hydraulic network modeling. The chapter provides an overview of the two main approaches used in the field: demand driven analysis (DDA) and pressure driven analysis (PDA). Furthermore, the chapter examines the basic principles behind leakage modeling, and provides a fundamental mathematical understanding of the relationship between pressure and leakage.

- Chapter 6 examines the WDNetXL HNSM which is used in the E^3 project. The model modules and their associated interface is briefly presented, together with the characteristics of the E^3-network model.
- Chapter 7 explains the method that is used to refine the existing E^3-network model.
- Chapter 8 presents the results obtained in the model refinement and discusses the uncertainties related to the work of the thesis.

Chapter 2
Digital vulnerability

2.1 Introduction

In recent decades, digitalization has led to pervasive societal changes. Increasingly, interaction between different services and exchange of information takes place through electronic communication. It has streamlined the workflow for most of us, so that the same work can be carried out with less effort. The way we manage processes of complex operations and infrastructures has also been altered, as they can now be controlled from one or a few key locations. Norway is one of the leading countries in the world on the use of ICT, as ICT systems and networks are the basis for process control and monitoring of installations on the Norwegian continental shelf, e.g. in power plants, water works, and eventually most parts of the industry. This makes the Norwegian industry more competitive and increase the overall productivity and innovativeness of the society as a whole. But the increased digitalization requires that the technology is safe to use.

The major technical changes of the society has led to security threats, and electronic communication impose new vulnerabilities that needs to be addressed in order to safeguard key societal services. Our ability to keep information confidential is challenged, and thus privacy. Operations and infrastructures are exposed to real threats related to the equipment they use. The equipment may be subject to an attack, and as a result it may be partially controlled by unauthorized users. In order to address the security issues of digitalization, The Norwegian Government has introduced laws and regulations, and also introduced the term "critical infrastructure".

2.2 Security of critical infrastructure

Critical infrastructure is defined as the assets and systems that are essential to maintain the critical functions of the society, which again involves the basic needs of society and the population’s sense of security (Direktoratet for samfunssikkerhet og beredskap, 2012). It is the concept of critical functions that is most central to an understanding of the area. The concept is linked to the basic needs of the society, which was defined by Abraham Maslow in his hierarchy of needs. The definition has been used by The Norwegian Government and comprises safety for the individual and basic physical needs, e.g. water and food. Critical societal functions involves assets and systems in which the society cannot do without for seven days without threatening the basic needs (Direktoratet for samfunssikkerhet og beredskap, 2012). There are strict safety requirements for anything concerning these assets and systems. In this context, cyber security means measures to protect information processed by an information system. This includes protection against breaches of confidentiality, integrity and availability, and also protection of the system itself and networks where information may be exchanged.

2.3 Digital security in the water sector

Safe water supplies are increasingly dependent on robust digital systems. Today, the water supply systems are controlled and managed via SCADA systems, line databases, access control and a range of other ICT-based systems. Increasing use of operational control in the operation of water and sewage systems provide improved monitoring and control and also increased efficiency, reliability and productivity. However, the digitalization impose new kinds of dangers and threats to the water sector.

The society expects that the water supply is robust, meaning it is expected that the waterworks are able to supply enough water at all times although the water supply system is exposed to various types of threats, e.g. the challenges arising from digital vulnerabilities. Water supply are therefore among the assets and systems that has been categorized as critical infrastructure by The Norwegian Government. The ICT systems of VAV is also regarded as a critical ICT infrastructure, since they are an integral part of the water supply system and can be regarded as a separate infrastructure within the water infrastructure. By law, the responsibility for the protection of the assets and the system lies with the owner or operator of the critical infrastructure (regjeringen.no, 2016). This means that VAV has the overall responsibility for the security of the water supply system in Oslo.

The Norwegian Government have established guidelines when it comes to securing ICT systems and the information contained in these systems. It can be broken into three different focus areas (regjeringen.no, 2016):

- **Confidentiality**: Means ensuring that information is accessible only to those authorized to have access. Examples of loss of confidentiality is that attackers access confidential information stored in the operational control, or that data go astray.

- **Integrity**: Means to ensure that the information, methods and calculations are accurate and complete. Unauthorized users can not change information of the system that processes information.
- **Availability**: Means ensuring that authorized users have access to information and associated assets when required. An example of loss of availability is that the operators are unable to log into the system and change the values if necessary. Availability may also allude the ability a water treatment plant has to supply clean water according to regulations.

2.4 Working with Oslo Water and Sewerage Works

The new guidelines, laws, and regulations in relation to increased cyber security for the water sector have created major complexity in handling data to and from VAV. The agency are constantly working with adjusting its practices for meeting the new requirements. As an unauthorized user, this meant I had to apply for permissions for every system I needed access to. Another consequence is that I have had to follow strict restrictions for what I was allowed to include in the thesis, and what not.

Chapter 3

Online monitoring

3.1 Introduction

Asset management can be defined as the coordinated activities of an organization to realize value from assets (ISO 55000, 2015). An asset is defined as an item, thing, or entity that has potential or actual value to an organization. By combining engineering and mathematical analysis with sound business practice and economic theory, the goal is to make the best decisions about organizations physical assets through their entire lifecycle (Ugarelli et al., 2010). This means increasing the assets efficiency, effectiveness and value.

Infrastructure asset management (IAM) can be described as an integrated set of processes to balance the life-cycle cost of infrastructure assets, at an acceptable level of risk, while continuously delivering established levels of service (National Association of Clean Water Agencies, 2015). Water IAM aim to accommodate the main challenges of urban water sectors, such as urban development, climate change, and ageing infrastructure.

The water infrastructure is built up by an enormous amount of individual components (pipes, pumps etc.) that together forms large systems, such as a water distribution system. One of the problems in such a system is that the components do not deteriorate at a constant rate, and therefore have to be replaced at different times. It's important that water utilities know that any intervention on an individual component will impact the whole system. Condition monitoring and assessment aim at providing a toolbox for water utilities to know when and where to replace components within the system. Condition monitoring means to monitor and maintain the assets of value by systematic data collection. Condition assessment is the evaluation of performance corresponding to the detected conditions of a system or its components. Both these actions happen in real-time. Preventive measures are assessed on the basis of condition-based deterioration models. They aim at planning remedial action in a cost effective manner to maintain reliability by predicting future conditions and corresponding performance.

3.2 SCADA systems

The earliest control networks were simple point-to-point networks connecting a monitoring or command device to a remote sensor or actuator (Igure et al., 2006). With the introduction of digital computers in the 1960s, remote terminal units (RTUs) were developed to collect real time measurements in energy networks through dedicated transmission channels to a central computer equipped with the capability to perform necessary calculation for automatic generation control (Wu et al., 2005). It was later applied to water distribution networks, focusing on measuring flows, pressure, pump status, valve conditions and other essential information. The aim was to have complete overview of the operation of the network. This enabled the water utilities to send command signals remotely from the control center to perform operational changes, for example to open or close valves in the network. This was called a SCADA system. In the 1990s, the focus of SCADA systems expanded to include other application functions. Some of the specific liquid pipeline applications were; real-time pipeline models, leak detection, batch tracking based on hydraulic modeling, or flow or volumetric metering, and power optimization (Ashton and Nagala, 2004).

SCADA systems are used to control and monitor distributed assets in systems where centralized data acquisition is as important as control. These systems are typically applied to different types of distribution systems, such as water and wastewater systems, oil and gas pipelines, electrical utility transmission etc. The aim is to provide a centralized monitoring and control system for process inputs and outputs by integrating data acquisition systems with data transmission systems and human-machine interface (HMI) software. SCADA systems are designed to collect field information and transfer it to a control center, where the information is displayed graphically or textually. This enables the operator to monitor or control an entire system from a central location in real-time. Operator commands can control and operate any individual system, or the tasks can be fully automated. The control center is therefore the central nerve system of a modern WDS. It gives a full overview of all the aspects of the system, adjusts its condition, coordinates its movement, and provides protection against exogenous events.

The implementation of SCADA systems has revolutionized the water industry, giving water utilities outstanding opportunities to monitor all parts of both water production and distribution from a centralized control center.

3.2.1 Components

Following is a list of major control and network components in a typical SCADA network. The list is retrieved from NIST (National Institute of Standards and Technology, U.S. Department of Commerce).

Control components

- **Control server:** The control server hosts the supervisory control software that is designed to communicate with the lower-level control devices. The server accesses the subordinate control modules over a SCADA network.
- **SCADA server or Master terminal unit (MTU):** The SCADA server is the master in the SCADA system. RTUs and PLCs usually act as slave devices.
- **Remote terminal unit (RTU):** The RTU is a special purpose data acquisition and control unit designed to support SCADA remote stations. RTUs are field devices often equipped with wireless radio interfaces to support remote situations where wire-based communications are unavailable.
- **Programmable logic controller (PLC):** The PLC is a small industrial computer that is designed to perform the logic functions executed by electrical hardware. They have evolved into controllers with the capability of controlling complex processes, and they are used substantially in SCADA systems. Programmable logic controllers (PLCs) are often used as field devices because they are more economical, versatile, and configurable than RTUs.
- **Intelligent electronic device (IED):** IEDs are smart sensors or actuators, which has the intelligence required to acquire data, communicate to other devices, and perform local processing and control. The use of IEDs allows for automatic control at the local level.
- **Human-machine interface (HMI):** HMI is a software or hardware that allows operators to monitor the state of a process under control, modify control settings to change the control objective, and manually override automatic control operations in the event of an emergency. It also allows operators to configure set points or control algorithms and parameters in the controller. The HMI displays process status information, historical information etc., and could for instance be a dedicated platform in the control center, a laptop on wireless local area network (LAN), or a browser on any system connected to the internet.
- **Data historian:** The data historian is a centralized database for logging all process information within the SCADA system. This information can be used to support various analyzes.

- **Input/output (IO) Server:** The input/output (IO) server is a control component responsible for collecting, buffering, and providing access to process information from control sub-components such as RTUs, PLCs, and IEDs. IO servers are also used for interfacing third-party control components, such as an HMI and a control server.

Network components

- **Fieldbus network:** The fieldbus network links sensors and other devices to a PLC or other controller. The need for point-to-point wiring between the controller and each device is eliminated using fieldbus. A protocol is used for communication between sensors and the fieldbus controller. The messages sent between the sensors and the controller uniquely identify each of the sensors.
- **Control network:** A control network connects the supervisory control level to lower-level control modules.
- **Communication Routers:** A router is a communication device that transfers messages between two networks. For SCADA networks, routers usually connect local area network (LAN) to wide area network (WAN), or MTU to RTUs.
- **Firewall:** A firewall protects devices on a network by monitoring and controlling communication packets using predefined filtering policies.
- **Modems:** A modem is a device used to convert between serial digital data and a signal suitable for transmission over a telephone line to allow devices to communicate. They are often used in SCADA systems to enable long-distance serial communications and for gaining remote access for operational functions.
- **Remote Access Points:** Remote access points are distinct devices, areas and locations of a control network for remotely configuring control systems and accessing process data.

3.2.2 Architecture

SCADA systems consist of both hardware and software. General SCADA system hardware includes an MTU placed at the control center, communications equipment, and one or more geographically distributed field sites consisting of either a RTU or a PLC. This hardware is necessary for the transfer of information data back and forth between the MTU and the RTUs/PLCs. The software within the system is designed to tell the system what and when to monitor, and programmed to know what parameter ranges are acceptable, and how to respond when parameters go outside the acceptable values. IEDs can communicate directly to the SCADA master station, or they may report to a local RTU or PLC, which sends the data to the master station. IEDs provide a direct interface to control and monitor sensors or actuators in the network, and they can usually collect and transfer data without specific instructions from the SCADA control center.

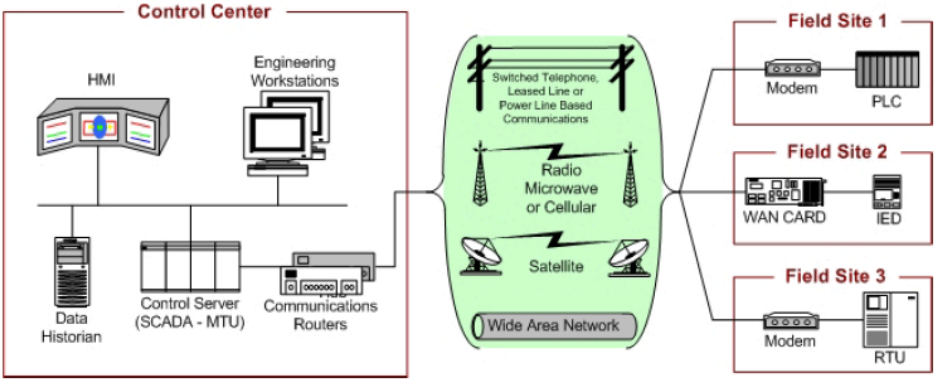


Figure 3.1: General layout of a SCADA system *(NIST)*.

The control center in a SCADA system houses a control server (MTU) and the communication routers. A HMI, the data historian, and engineering workstations are also stored within the control center. These components are all connected by a LAN. Figure 3.1 shows how these components are connected in a general architecture of a SCADA system. Information that is gathered by the field sites are logged and controlled in the control center, and displayed to the HMI. Detection of abnormal events will cause the control center to generate counteractions. Other tasks of the control center are to analyze trends in the system and generate reports. The field sites in the system perform local control of actuators and monitors sensors. Field operators often have remote access to perform diagnostics and repairs over a separate dial up or WAN connection through the field sites.

MTU-RTU connection architecture may vary among different implementations. Figure 3.2 shows the most common set ups; point-to-point, series, series-star, and multi-drop. Figure 3.3 shows a typical topology for large SCADA systems.

3.2.3 Communication

SCADA systems are complex networks that support communication between a central control unit and multiple remote units on a common communication bus. The remote units are usually special purpose embedded computing devices such as sensors and actuators, or PLCs. These sensors send information to computers with SCADA

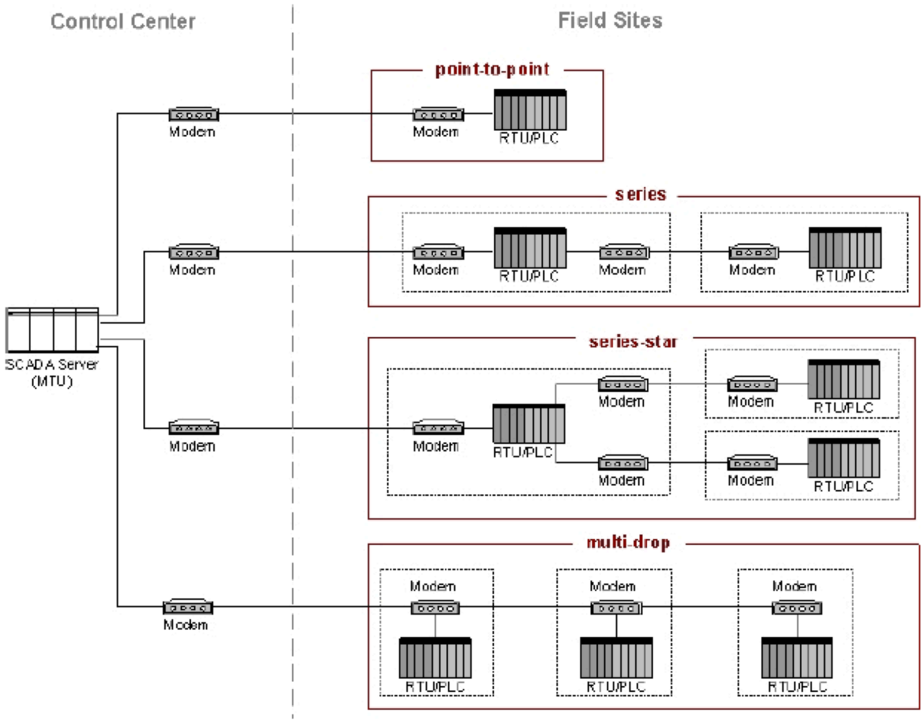


Figure 3.2: Basic SCADA communication topologies *(NIST)*.

software, which analyzes and displays the data in order to help operators to reduce waste and improve efficiency in their system.

Traditional SCADA networks are made up of master and slave devices. They exchange control messages and are responsible for the communication within the network. A master device is a device that can control the operation of another device. Personal computers (PCs), PLCs, and RTUs are examples of master devices. A slave device is usually a simple sensor or actuator, which is controlled by commands from a master device. It can also send information messages to the master device.

The RTUs in the network are monitored and controlled over the SCADA network. A RTU collect and process the data from substations before it sends the data through a dedicated communication channel with proprietary protocol to the appropriate data acquisition computer in the control center. The data is Transmission control protocol (TCP)/Internet protocol (IP) based, which is a communication protocol that is regarded as the standard for sending data in a network. An interface is needed for

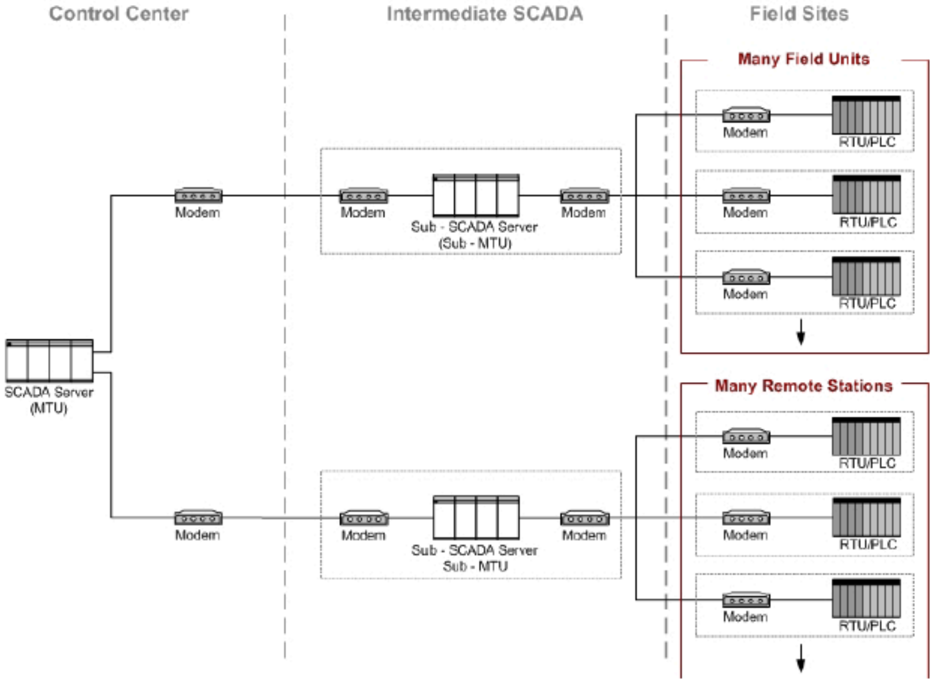


Figure 3.3: Large SCADA communication topologies *(NIST)*.

this reason. The data acquisition computer then converts the data and prepares it for deposition in the real-time database. This database is accessed and used by various applications. The interface may be handled by a telecontrol gateway, and more gateways may be used in a control center, in order to increase efficiency. The location of a gateway may be moved to a substation and connected to the control center if a standard IP control is used. If the RTU is TCP/IP based, it can be connected directly to the control center resulting in a distributed data acquisition system. The gateway then serves as a data concentrator and communication processor, which can connect the RTUs to the control center. RTUs may also be directly connected to the control center (Wu et al., 2005).

Protocols, such as PROFIBUS, provide features for communication between fieldbus devices that want to communicate as peers. This includes a peer-to-peer communication model between master devices and a client-server communication model between master and slaves (Igure et al., 2006).

Communication between master and slave devices can sometimes be asymmetric

(Igure et al., 2006; Risley et al., 2003). This means that messages sent from the slave device to the master device can be much larger than the messages sent the other way. Some devices may also only be communicating through alarms and status messages. Protocols have been designed to give priorities to messages that come from devices that share a common bus, in order to distinguish between critical and non-critical messages from such devices.

Another feature that is important for SCADA protocols is that they ensure delivery assurance and stability. It is important that the critical messages are delivered within the time constraints of the system. Often, water distribution networks require real-time communication in case of emergency.

3.2.4 Security issues

Recent studies show that the number of attacks against SCADA networks has been escalating steadily over the years (Igure et al., 2006). Attackers aim to compromise the security properties such as integrity, confidentiality, authentication, and availability. In the early days of SCADA development, the focus was to provide good performance and the emphasis was placed on providing features that would ensure that the task constraints of the network could be met. Network security received little attention. As the demands for increased connectivity between the distribution system and the corporate network started to grow, so did the concerns about security in the SCADA system. The control network developed to no longer being isolated, but being a part of a more complex inter-network.

An important change of attitude was that physical isolation no longer was adequate to ensure network security. A phone line, or an intranet connecting the local network to the wider company network is all that is needed for a potential attacker to breach into the system, and potentially gain access to machines inside the distribution network. Also, the newly adapted open communication protocol standards for SCADA systems make it easy for attackers to gain in-depth knowledge about the dynamics of the system.

Another factor contributing to the security issue is the inclination to use commercial off-the-shelf (COTS) software and hardware in recent years. SCADA networks can now operate on traditional Ethernet networks and the TCP/IP stack. The protocols are often established serial-line based protocols wrapped up in some standard process before they are placed in a TCP packet. These protocols often abandon the master/slave principle that is normally seen in traditional SCADA networks. Devices that are designed for these networks often have additional application-layer interfaces, such as web-interface capability that can be coupled with the integration to the corporate network. The intention is to enhance information flow and gathering for higher-level management. However, these protocols become highly exposed to application-layer and TCP/IP based attacks.

An attacker who gains access to the SCADA network has the potential to carry out a range of attacks (Risley et al., 2003; Pollet, 2002). By intruding the network, an attacker could learn all the data, control the commands, send false messages to the devices in the network, tamper with the data transmitted in the network, and also block or reroute communications to cause significant denial-of-service attacks (Igure et al., 2006). This can cause significant financial losses due to loss of production capabilities, but it can also lead to loss of life as the human response to emergency can be delayed.

3.3 Monitoring tools - Aquis

Aquis is an advanced, water-specific, software that enables operators to optimize water distribution networks in real-time. The model is fed with live information from the SCADA system, which enables the software to predict future consumption. It is also able to predict consumption in changing weather conditions, as it also collects weather forecast information. This allows for predictive as opposed to reactive control of the water system. Resulting benefits can include improving water quality through reduced water age, minimizing energy cost and improved system operations without compromising operational reliability (Weber and Bunn, 2009).

The software is designed to give the operator full overview of a given distribution network, and attempts to provide operational understanding of bottlenecks and potential performance of the network. Effects of interventions, such as opening or closing of valves, can be assessed by intervention simulation, which reveal disturbances in consumer supply. The operator can also run scenarios of the network prior to initiating maintenance work, or run different operational modes before implementing them in the actual network.

The model has a claimed accuracy of 99%, and offers a range of different optimization modules that can be applied to specific fields of study within a water distribution system. The different modules are: water quality, leak detection in pipelines, pump and reservoir optimization, and pressure optimization.

3.3.1 Leakage detection module

The capability of the leakage detection and location module depends on the instrumentation of the distribution network. The module may either be embedded as a component in the SCADA system, or it can be used as a stand-alone system with data communication interface to the SCADA system. Leakage detection and location runs a dynamic real-time simulation model to generate leak responses. By doing this, it can work under all operating conditions. Customizable options for checking incoming measurements and emulating missing or faulty data is provided in order to ensure robust leak detection. The module also provides straightforward configuration of the system and clear presentation of results via the graphical user interface.

3.3.2 Pressure optimization module

The pressure optimization tool uses SCADA data from the water distribution network, and aims at minimizing leakage and operational cost. The module adjusts the inlet pressure to the minimum of what is required to ensure that the right amount of water is supplied to the consumers in the net. Pressure optimization in the module takes into account the fluctuation of consumption in the net, and common operational changes, such as valves being opened or closed, or variation at weekends and holidays, to provide set-points for the pumps or pressure control valves. It also includes unusual operational interruptions in the calculation. The Aquis Real-Time functionality can be added to the module, providing full dynamic presentation of pressure, consumption and flow in the network. It is claimed that the pressure optimization module helps reduce leakage by 10-15%, and also reduce associated cost such as pumping cost and chemical treatment of the water.

3.3.3 Pump and reservoir optimization module

The Aquis pump and reservoir optimization module takes use of an optimization algorithm that is based on the dynamic programming technique, and aims at reducing both energy consumption and CO2 emission. It is possible to determine the optimal pumping schedule for a pipeline system for a given, user defined, period of time. The module takes into account demand schedules, power costs, current levels in reservoirs, pump characteristics among other things, and claims that a total electric- and CO2 emission saving of 10-15% can be achieved. Data may be retrieved from a SCADA system, and set point for each pumping station can also be sent back to the same system.

3.3.4 Water quality module

The Aquis water quality module can track water throughout the water distribution network and provides and overview of the chemical composition in every part. It aims at predicting and limiting the spread of pollution, and also to identify the pollutant source. Online data is transmitted through an online analyzer via a SCADA system. Once an analyzer exceeds an alarm you are able to track the spreading of water from that point and further into the distribution network. Suggestions are then made on which valves to close to limit the spreading. Also, extrapolation of the online data measuring points identifies the most likely source of contaminants.

3.3.5 Security issues

Commercial off-the-shelf (COTS) software and hardware, such as Aquis, can contribute to the lack of security in SCADA networks. These design solutions often save cost and reduce design time, but it also raises concerns about the overall security of the end product. They are often not very secure, and therefore they are tempting targets for attackers. Devices that are meant to operate in safety-critical environments are usually designed to fail-safe. However, security vulnerabilities could be exploited by an attacker to disable the fail-safe function (Igure et al., 2006).

Chapter 4

Retrieving data from the historian database

4.1 Introduction

One of the objectives of this thesis is to analyse the specifications of a SCADA system to be able to retrieve consistent data, in the right format, in order to calibrate hydraulic models. The SCADA system of VAV has been used as an example, because of the related work that has been done in conjunction with the E^3WDM project (see chapter 1). This chapter describes the theoretical and practical aspects regarding information and data retrieval from the system.

4.2 SCADA system of Oslo Water Works

As explained in chapter 2, a lot of the work of Oslo Water Works is security graded, and the same applies to their SCADA system. Therefore, the system is briefly described in this section.

Many measuring points and field sites are located in the WDS of Oslo. Almost all sensors and meters collects pressure and flow data.Therefore, the system employs sub-MTUs to alleviate the burden of the primary MTU. The topology of the SCADA system follows a general layout for a large system, similar to the architecture described in subsection 3.2.2 and shown in figure 3.3 on page 17. The field sites are connected to the intermediate SCADA sites and to the control center by WAN. This is because VAV regards it as more efficient and reliable than telephone lines, radio, and satellite. PLCs are used to a greater extent than RTUs. The reason is that PLCs are more economical, versatile and configurable than RTUs (Stouffer et al., 2011).

All the information that is collected in the field sites are stored in the historian, as shown in Figure 4.1. This information is used to control and monitor the trends within the system. A HMI displays process status information and historical information, e.g. instantaneous flow and pressure and historical values. The HMI in use at VAV is called iFix. This system allows operators to monitor the state of a process under control, modify control settings to change the control objective, and manually override automatic control operations in the event of an emergency. It also allows operators to configure set points or control algorithms and parameters in the controller.

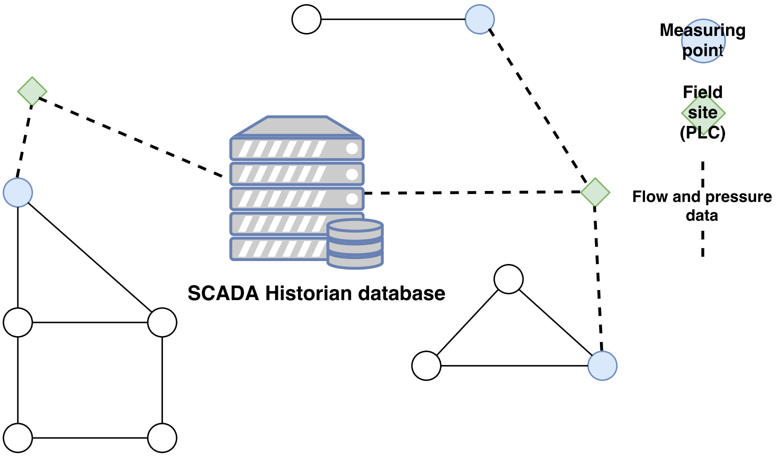


Figure 4.1: Flow and pressure data is sent from a measuring point in the network to the historian via a field site.

4.2.1 E^3WDM network

The WDS of E^3WDM consists of approximately 5812 pipes and 5440 nodes. The E^3WDM network has 40 measurement points, with sensors and meters that collects various data. Almost all the points measure collects pressure and flow. These data can be used in a number of ways (some are explained in chapter 3 and chapter 5).

4.3 Retrieving data

The existing systems of VAV for collection, processing and logging data has been used in this thesis. This is partly done to show that the amount of continuously recorded data can be exploited in a good way, and partly to ensure the security of the system. Data retrieval has been done through the iFix system and iHistorian. Locations, measurement frequencies, measurement descriptions, and other details about the field sites has been collected from archives, iFix, and from VAVs Arcmap database.

4.3.1 Explanation of terms

- **Measurement**: A measurement by a meter or a sensor, e.g. a pressure value from a pressure meter or a temperature from a temperature sensor. A measurement usually contain a timestamp and a value.

- **Measuring point**: A node in which a meter or sensor is located. This could be a standalone meter/sensor placed in a manhole, or a meter/sensor in relation to a water pump, pressure tank, or pressure reduction valve.
- **Logged data**: A data package containing information about a measurement that is successfully sent to the field site and SCADA control center, and later stored in the historian.
- **Data retrieval**: The process of retrieving logged data from the historian database.
- **Sample**: A section of logged data, e.g. a day, a week, or a month.
- **Time interval**: The time resolution of a given sample.

4.3.2 Proficy Historian

Proficy historian (hereinafter iHistorian) is a supplementary program for iFix for use in spreadsheet programs such as MS Excel. iHistorian is used to retrieve data from the historian in VAVs SCADA system. The program is able to retrieve both long time series and real-time data (Friedenthal, 2007).

4.3.3 Sampling methods

There are several different ways to retrieve information from the historian. The four options in iHistorian is: lab sampling, trend sampling, interpolated sampling, and raw sampling (Friedenthal, 2007).

Lab sampling

Lab sampling retrieves raw data. Raw data is the actual data that is logged in the SCADA field site, which means that the data is not treated in any way. The sample is evenly spaced by a user selected interval. For each interval it returns either a raw sample that was stored at the time, or the last good value that was stored. This sampling method is commonly used to trend raw data when interpolation is not desirable. Since lab sampling returns actual logged values, it is more accurate when a sufficient number of raw samples are stored.

Trend sampling

Trend sampling retrieves the raw minimum and the raw maximum of logged data for each user specified time interval. The sampling technique divides the time interval in half and returns the highest or the lowest value, depending on whichever occurred first, for the intermediate time sample. A high-low pair for each time interval ensures that no maxima or minimum is missed regardless of the sample interval. The technique is commonly used to get an overview of a process with only a small sample of data.

Interpolated sampling

Interpolated sampling retrieves data spaced on intervals other than what is actually logged. An evenly spaced sample of the most likely real-world values is produced by using an interpolation between raw samples (see subsection 4.3.6). This sampling method is commonly used to retrieve logged data that is not stored at even time intervals, or if it desirable to display the data at a higher resolution than what is actually logged.

Raw sampling

Raw sampling retrieves the actual logged data, regardless of the quality. This means that periods were no data logging has occurred is returned as a bad value, and not as an interpolated value. This is the difference between a lab sample and a raw sample. It is primarily used to access the raw, unfiltered data, which gives an actual overview of a given process. The data can then be treated as desired by the user after retrieval.

4.3.4 Tag names

Each node that has a pressure and/or flow meter is referred to as a measuring point. Every measuring point has different *tag names*, which is the names of specific measurements at the point in the SCADA historian server. Therefore, the tag name is used to retrieve desired data. The tag name always include an abbreviation that explains the type of the measuring point, as shown in Table 4.1. Each measuring point also have a description and an engineering unit of the measurement attached to its tag names in the historian. This is shown in Table 4.2, where MK104 is used as an example.

Abbreviation	**Meaning**
RK	Pressure reduction valve
HB	Pressure tank
VP	Water pump
MK	Manhole equipped with pressure and/or flow meter

Table 4.1: Abbreviations for measuring points as they are stored in the historian database.

Tag name	Description	Engineering units
VAV1.MK104_FQ1_FRAM_SD.F_CV	Accumulated last day	m^3
VAV1.MK104_FQ1_FRAM_ST.F_CV	Accumulated last hour (F_CV)	m^3
VAV1.MK104_FQ1_TILBAKE_SD.F_CV	Accumulated last day	m^3
VAV1.MK104_FQ1_TILBAKE_ST.F_CV	Accumulated last hour (F_CV)	m^3
VAV1.MK104_FT1_FRAM_GT.F_CV	Average flow last hour	l/s
VAV1.MK104_FT1_FRAM_VERDI.F_CV	Flow towards Lambertseter (instantaneous)	l/s
VAV1.MK104_FT1_TILBAKE_GT.F_CV	Average flow last hour	l/s
VAV1.MK104_FT1_TILBAKE_VERDI.F_CV	Flow towards Skullerud (instantaneous)	l/s
VAV1.MK104_PT1_ST.F_CV	Mean value last hour (F_CV)	bar
VAV1.MK104_PT1_VERDI.F_CV	Instantaneous value (F_CV)	bar
VAV1.MK104_PT1_VERDI1.F_CV	Instantaneous value (F_CV)	bar
VAV1.MK104_PT1_VERDI2.F_CV	Instantaneous value (F_CV)	bar
VAV1.MK104_TT1_VERDI.F_CV	Instantaneous value (F_CV)	°C

Table 4.2: Tag names and descriptions for MK104 (Oslo Water and Sewerage Works (VAV), 2016).

As we can see from Table 4.2, there are several tag names belonging to MK104. In MK104, the flow is measured in two directions, and the pressure is measured multiple times by the same meter. Some of the values displayed in the table are automatically calculated and stored in the historian, e.g. accumulated flow, average flow, and mean value. The instantaneous value is the real time measurement of the pressure and flow. Figure 4.2 shows a schematic of the manhole MK104, and includes the location of the pressure and flow meter, and the temperature sensor.

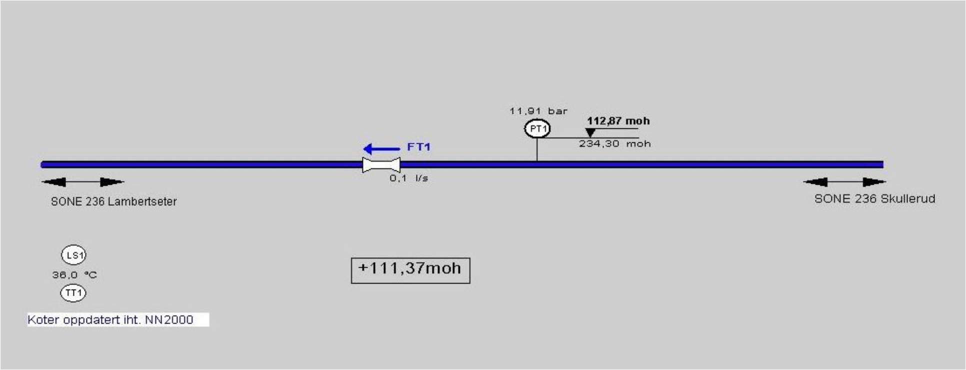


Figure 4.2: The layout of MK104 and its pressure and flow meter. FT1 refers to the flow meter, PT1 to the pressure meter, and TT1 to the temperature sensor (Oslo Water and Sewerage Works (VAV), 2016).

4.3.5 Data quality

It is important to note that logged data is not typically stored at even intervals. The quality of the logged data is often varying throughout a sample period. Therefore, logged data is classified as either "good" or "bad". "Bad" values are either uncertain, meaning they are abnormal compared to previous loggings, or they are not existing, due to system failure, e.g. faulty communication to the PLC at the field site or breach of a 4-20 mA current loop (Oslo Water and Sewerage Works (VAV), 2016). Table 4.3 displays raw data values retrieved from MK104.

Timestamp	**Value**	**Timestamp**	**Value**
02-mai-16 00:01:00	6,275272846	02-mai-16 00:16:00	13,56527042
02-mai-16 00:02:00	10,53711796	02-mai-16 00:17:00	22,42542076
02-mai-16 00:03:00	5,938811302	02-mai-16 00:18:00	18,38788414
02-mai-16 00:04:00	7,284657001	02-mai-16 00:19:00	14,23819351
02-mai-16 00:05:00	8,06973362	02-mai-16 00:20:00	11,99511719
02-mai-16 00:06:00	9,191271782	02-mai-16 00:21:00	13,22880936
02-mai-16 00:07:00	10,31280994	02-mai-16 00:22:00	Bad
02-mai-16 00:08:00	11,43434811	02-mai-16 00:23:00	14,0138855
02-mai-16 00:09:00	8,630502701	02-mai-16 00:24:00	Bad
02-mai-16 00:10:00	8,406195641	02-mai-16 00:25:00	13,34096241
02-mai-16 00:11:00	8,966963768	02-mai-16 00:26:00	Bad
02-mai-16 00:12:00	Bad	02-mai-16 00:27:00	15,58403873
02-mai-16 00:13:00	8,06973362	02-mai-16 00:28:00	14,79896259
02-mai-16 00:14:00	9,752040863	02-mai-16 00:29:00	13,56527042
02-mai-16 00:15:00	10,87357903	02-mai-16 00:30:00	17,15419197

Table 4.3: Raw data retrieval from MK104 on 02.05.2016 (Oslo Water and Sewerage Works (VAV), 2016).

"Bad" values can occur quite often when raw data is retrieved, as shown in Figure 4.3. It is very important to note that a “bad” value is not the same as 0. There is a flow and a pressure occurring, but it is not logged and stored in the historian as a value. This needs to be taken into account in the data treatment process.

4.3.6 Data treatment

Logged data can be treated in a number of ways. The basic options is to perform a calculation on the data in the retrieval process, or to retrieve the raw data and treat them afterwards, as shown in Figure 4.4. Raw data refers to the actual, unfiltered data that is logged in the system. Logged values are returned regardless of their

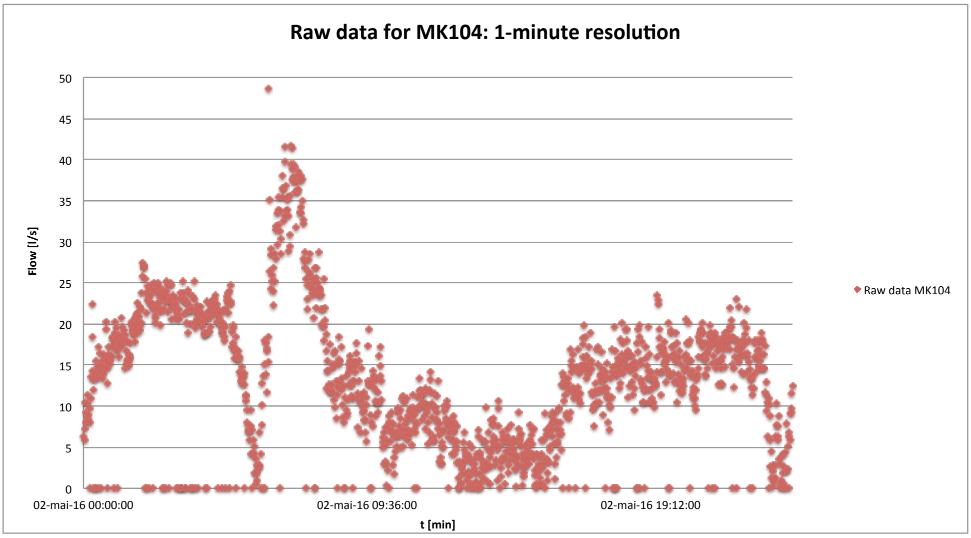


Figure 4.3: Scatter plot from a raw data retrieval from MK104 on 02.05.2016. All points at the baseline are not actual zeros, but "bad" values. The data has been retrieved at intervals that corresponds to the actual logging times of MK104 (Oslo Water and Sewerage Works (VAV), 2016).

quality. A "bad" value is simply returned as "bad" (see Table 4.3). As for the other alternative, there are three basic options for performing a direct calculation in the iHistorian: interpolation, average, or a combination of the two.

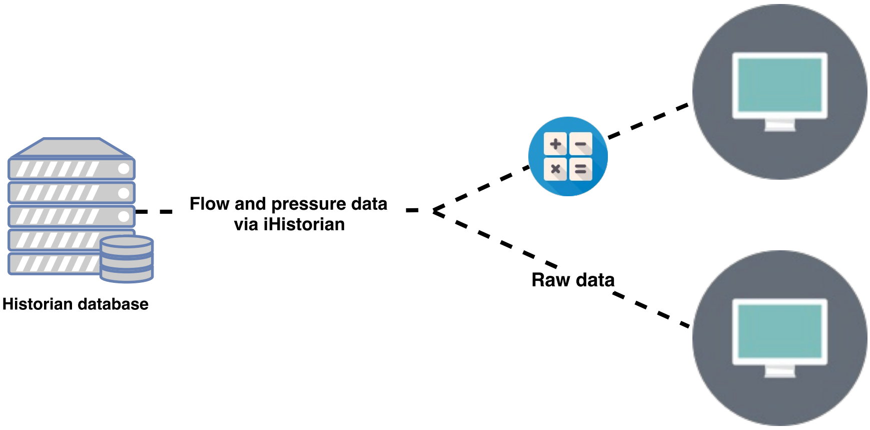


Figure 4.4: Logged data can either be retrieved as raw data, or a calculation can be performed in the retrieval process.

Interpolation

Interpolation is a method of constructing new data points within the range of a discrete set of known data points. It can be useful when the sample period consists of periods where no data is stored. The known data points is then used to estimate (interpolate) an intermediate value to create a complete data set for the given time interval. Interpolation is the only tool that can help create continuous data series for discrete values. iHistorian takes use of linear and polynomial interpolation.

If two known points are given by the coordinates (x_0, y_0) and (x_0, y_0) the linear interpolant is the straight line between these points. For a value x in the interval (x_0, x_1), the value y from the straight line is given from the equation:

$$\frac{y - y_0}{x - x_0} = \frac{y_1 - y_0}{x_1 - x_0} \tag{4.1}$$

Solving this equation for the unknown, y, gives:

$$y = y_0 - (y_1 - y_0)\frac{x - x_0}{x_1 - x_0} \tag{4.2}$$

Which is the formula for linear interpolation. The continuous lines in the left graph in Figure 4.5 are constructed using linear interpolation.

Polynomial approximation can be written in many different forms, depending on the usage, e.g. Taylor and Newton Polynomials. However, iHistorian takes use of polynomial interpolation in the Lagrange form. Suppose that a polynomial is in the form:

$$p(x) = a_n x^n + a_{n-1} x^{n-1} + \cdots + a_2 x^2 + a_1 x + a_0 \tag{4.3}$$

An interpolant $p(x)$ can be written so that $p(x_i) = y_i$ for all $i \in \{0, 1, ..., n\}$:

$$\begin{aligned} p(x) = \quad & \frac{(x-x_1)(x-x_2)\cdots(x-x_n)}{(x_0-x_1)(x_0-x_2)\cdots(x_0-x_n)}y_0 \\ + \quad & \frac{(x-x_1)(x-x_2)\cdots(x-x_n)}{(x_1-x_1)(x_1-x_2)\cdots(x_1-x_n)}y_1 \\ \vdots \quad & \\ + \quad & \frac{(x-x_1)(x-x_2)\cdots(x-x_n)}{(x_n-x_1)(x_n-x_2)\cdots(x_n-x_n)}y_n \end{aligned} \tag{4.4}$$

Which is the basic formula for polynomial interpolation in the Lagrange form. Figure 4.5 shows the difference between a line constructed from a linear and a polynomial interpolation. Linear interpolation is in fact a special case of polynomial interpolation with two points.

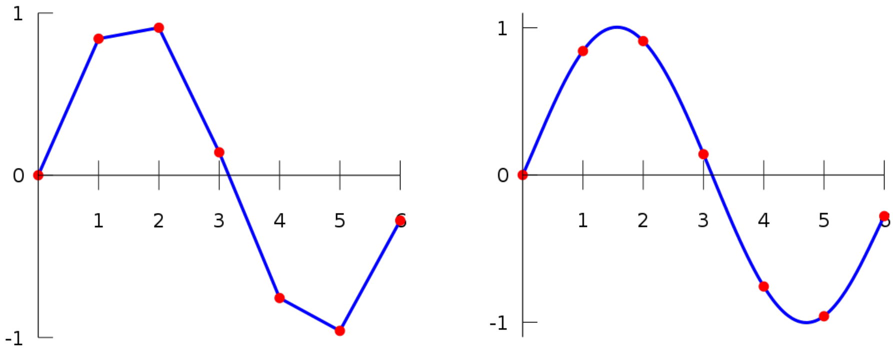


Figure 4.5: Linear (left) vs. polynomial (right) interpolation (wikipedia.org, 2016).

Average

iHistorian is able to calculate the arithmetic average of raw data to produce evenly spaced samples. An average is a statistical measure of central tendency. The arithmetic average is defined as being equal to the sum of the numerical values of each and every observation divided by the total number of observations. If we have a data set from the historian with values $a_1, a_2, ..., a_n$, the arithmetic average can be written as:

$$A = \frac{1}{n}\sum_{i}^{n} a_i \tag{4.5}$$

This is usually done to create evenly spaced sample series from raw data. The values that are logged are then summed together and divided by the total number of measurements.

Combination

It is also possible to create evenly spaced samples from averaging the values, and then perform an interpolation afterwards. Figure 8.5 is an example where this is done to create a transparent graph.

Chapter 5

Hydraulic network simulation models

5.1 Introduction

The purpose of a WDS is to supply enough water to satisfy consumer needs when it is necessary, at adequate pressure, and with the right quality. Increasingly, leakage is acknowledged as one of the main challenges facing water utilities. Leaks and bursts in the network cause significant water and revenue losses. Therefore, the analysis of pipe deterioration and the corresponding increase in water loss should be an integral part of any medium- to long-term rehabilitation planning for a WDS. A mathematical model that is able to simulate the system's behavior as closely as possible is a great advantage for operational purposes.

HNSMs have been well-developed and applied to water distribution systems over the last three decades. Such models are now widely used by stakeholders that are involved in the analysis, design, operation, and maintenance of a water distribution system.

A WDN model is designed to represent an actual WDS. It reflects the pipeline system and facilities, such as sources, pumping stations, storage reservoirs, valves, and other control equipment. The level of detail captured in the model needs to reflect the problem being analyzed. For example, a detailed model may be needed if one is studying the connectivity, density, sizing and location of valves in a distribution system from a reliability point of view. On the other hand, a reliability study of supply in whole zones in the system may only need a basic model of the facilities and the major transmission system (Wagner et al., 1988).

It is important to note that although a HNSM is designed to represent an actual WDS, it can only be regarded as a simplification of the real system. The model is designed to simulate the principal behaviour of the system, and can be used for different purposes, including analysis of the most important system parameters (e.g. pressure, flow), and also prediction of the expected behaviour of the system.

HNSMs are built based on the link-node formulation, in which links are interconnected at nodes. Water consumption that occurs along links is transferred to their end nodes, and defined as nodal demand. This nodal demand aggregates water consumption that can be pressure-independent (volume based) or pressure-dependent (the flow provided to consumers depends on the available hydraulic pressure) (Muranho et al., 2014).

5.2 DDA (Demand Driven Analysis)

Models that are pressure independent are usually referred to as demand-driven models (DDMs). The discharge of flow in pipes and nodal pressures are evaluated with hydraulic simulation due to the conditions of the network. In DDMs the nodal outflows are assumed constant irrespective of the network pressures, and it is the current demand that drives the model (Tabesh et al., 2011). The demands are fixed, and known, (i.e. from field observations) at any time step. Analysis based on this assumption is known as DDA. Most well-established analysis models are based on this approach. It is important to emphasize that the assumption of demand independency on network pressure status is instrumental to model simplification and holds as a statistical assumption.

Urban water demands are divided into different categories. The demands that have specific volumes, such as clothes-washing machines, dish-washing machines, bath tubs and flushes in households etc., are called volumetric demands and their relative discharges are called volumetric discharges. These demands are unlikely affected by nodal pressure. After supplying the required volume, no more discharge is necessary (Tabesh et al., 2014). DDA is a reasonable approach for these types of demand, under normal operating conditions, when the pressure at each node is satisfactory.

Leakage is pressure dependent. This means that the water loss in a network increase with an increased pressure. Especially at times where human demand is low while the energy level at the system is kept constant, i.e. if the system has a constant pumping regime or no pressure regulation in any form. Leakage is a pressure dependent demand that is usually modeled in two different ways in DDMs: either as a constant percentage of the fixed nodal demands, or as a nodal emitter flow. Emitters are devices that model flow through a nozzle or orifice that discharges to the atmosphere. The flow rate through the emitter is defined as a power function of the nodal pressure using an emitter coefficient and an exponent. Emitters are usually used to simulate fire hydrants, but they can also be used to model pressure-dependent demands. The problem with this approach, however, is that they produce wrong results in situations where the nodal pressure is negative or less than satisfactory. An emitter flow can also be infinitely large, which also contributes to unrealistic results (Muranho et al., 2014).

The DDA approach has some limitations, mostly due to the fact that leakage is pressure dependent. The algorithms used within the model cannot handle situations where the pressure in a demand node is less than satisfactory due to pipe failures or excess of demands. Also, demand driven tools are incapable of simulating pressure deficient conditions properly, because they assume leakage proportional to nodal demand at each node, but independent of network nodal pressure. This leads to unrealistic nodal leakage estimates.

There are at least two major drawbacks using the assumption of a constant leakage percentage normally employed with demand-driven simulation. The first one is that the resultant low leakage flows for nodes experiencing low demand, even if they experience high nodal pressure. The second one is that two nodes having equal demand will have equal leakage flow rates associated with them despite their actual hydraulic positions in the network (pressure levels) related to elevations, tank, and pump locations (Giustolisi et al., 2008).

5.3 PDA (Pressure Driven Analysis)

There are several factors and events that can affect the pressure conditions within a water distribution system. Valve failure, pump breakdowns, leakage, and improper design features within the system are some of them. There are also different demands that change proportional to the available pressure. Irrigation, washing, shower etc., are all demands that are pressure dependent, and their relative discharge are called pressure dependent discharges. In order to obtain a better estimate of the total flow through the network, with respect to both satisfied demand and losses, a pressure-driven hydraulic model is needed (Wu et al., 2009a). Pressure-driven simulation considers nodal outflows as variables that depend on the available pressure, and it is the current pressure that drives the model. Analysis based on this assumption is known as PDA.

Unlike the conventional water distribution model where the nodal demand is a known value, the pressure-dependent demand modeling approach stipulates that both the nodal demand and pressure are unknown. Models that are pressure dependent are referred to as pressure-driven models (PDMs). PDMs use a relationship between nodal demand and nodal pressure in order to simulate the behavior of the system. The reason is that nodal demands are not fixed in a real situation. They are related to nodal pressures. Different relationships have been suggested over the years, but the Wagner et al. equation has proved to be the most appropriate one (Tabesh et al., 2011, 2014; Wu et al., 2009b).

5.4 DDA vs. PDA

DDMs are more efficient than PDMs from both a numerical and a computational standpoint, since the demand-pressure relationship adds mathematical and numerical complexity to the modeling problem. However, it is the network working conditions that define the need of either a DDA or a PDA. A WDS can operate under normal working conditions or abnormal/pressure-deficient conditions.

Normal working conditions means that the pressures within the network does not drop below the designed minimum pressure limit. In this case, the hypothesis that the customer demand does not exceed the maximum required demand holds as a statistical assumption. It is also reasonable to assume that customers controls the orifice opening degree. DDA can be performed using a DDM in situations like these, and the leakages will then be fixed as a percentage of the statistical demands.

Abnormal working conditions can also be described as pressure-deficient conditions. In this case, the pressure drops below the minimum designed pressure at one or more nodes within the network. There can be many reasons for this, for example that the hydraulic resistance in the network increases or the topology changes due to planned or unplanned events. A PDA is necessary in situations like these. It is important to note that the pressure will not be below the minimum value for all nodes in the network. Since the locations of the pressure-deficient nodes are not known, it is effective to have continuity between PDM and DDM (Giustolisi et al., 2008; Laucelli et al., 2012).

Figure 5.1 shows the difference in pressure-demand curves for pressure-deficient and normal working conditions. The use of DDA and PDA is defined for both conditions.

5.5 Leakage modeling

A simulation model designed to analyze the reliability of a water distribution system usually consist of two parts (Wagner et al., 1988):

1. The simulation section, which generates failure and repair events according to specified probability distributions.

2. The hydraulic network solution section, which gives the flows throughout the network and the heads at each node for a specified demand in the completely or partially failed system. The model usually provides considerable flexibility in the failure probability distributions employed.

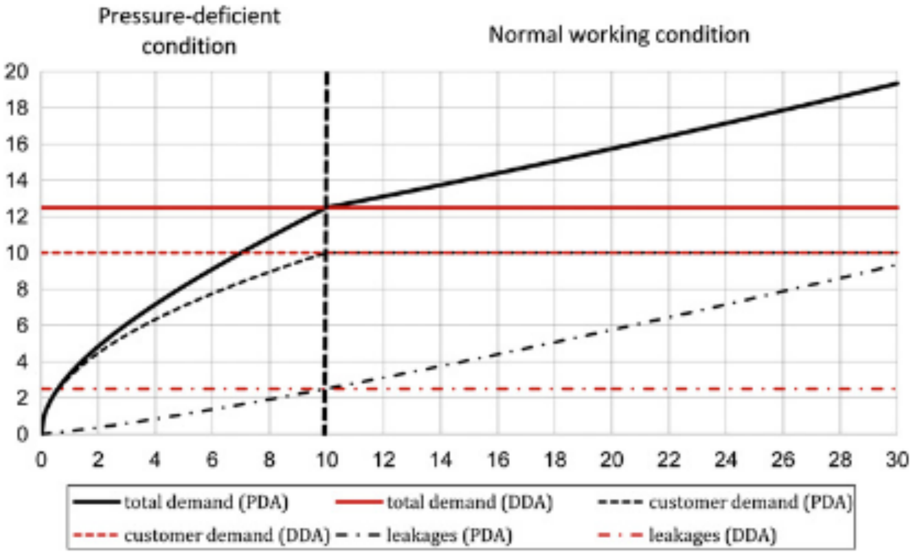


Figure 5.1: Difference in pressure-demand curves for pressure-deficient and normal working conditions. (Laucelli et al., 2012).

Several data is needed as input for the model to be able to analyze the system performance and reliability:

1. Network information:
    a) Topology.
    b) Length, diameter and roughness coefficient for each pipe.
    c) Pump curve for each pump.
    d) Geometry for each water tank.
    e) Valves on/off.
2. Demands and boundary conditions:
    a) Demands at nodes.
    b) Given heads at sources and tanks.
3. Failure and repair probabilities:
    a) Form and parameters for inter-failure time probability distribution function for each component that is subject to failures.

  b) Form and parameters of repair duration probability distribution function for each such component.

4. Total duration of the simulation time period.

The heads and flows throughout the system are obtained through calculation by the model. The model assumes that the system has no failures and creates a base condition, which serves as the foundation for further analysis. The simulation proceeds by randomly generating failure times of the pipes according to the specified failure time distributions.

In order to be as realistic as possible, the model also needs to model both background and burst leakage. Bursts are intended as major water outflow events that are usually reported to water utilities and repaired since they are likely to produce major service disruptions. Bursts are generally considered as accidents whose impact on water distribution networks can be limited by active leakage control and the efficiency of detection and repair actions. Background leakages are diffuse outflows from small cracks, holes or deteriorated joints or fittings along pipelines. These types of leaks do not result in evident and quick pressure drops in the network. This means that they are usually not reported, and therefore they run for a longer time, producing significant water losses. Models can take such leaks into account in the simulation by assuming a steady, pressure dependent, base flow out of the network. It is then considered as one of the demand components within the model (Berardi et al., 2015).

5.5.1 Leakage equations

It is of great importance to establish a relationship between the leakage of a pipe and the internal pressure of the pipe itself, in order to be able to model leakages in water distribution systems. There has been significant development in the understanding of the relationship between pressure and leakage based on the results of numerical, theoretical, experimental, and field studies, over the last 20 years (van Zyl, 2014).

Toricelli's and FAVADs equation

The conventional belief in the past was that leakage is relatively insensitive to pressure. A leak was considered as an orifice, and the general Toricelli equation made it possible to describe the relationship between the orifice and the pressure head on its centroid. The equation is given as:

$$Q = C_d A \sqrt{2gh} \tag{5.1}$$

Where Q is the flow rate through the orifice, C_d is the discharge coefficient, A is the orifice area, g is the acceleration due to gravity, and h is the pressure head differential over the orifice. This equation is derived for an orifice in the side of a tank and describes the conversion of all the potential energy, in the form of pressure, to kinetic energy. The discharge coefficient is added to incorporate energy losses and the reduction of jet diameter downstream of the orifice. The pressure in the jet downstream of the orifice is assumed to equal that of the surrounding fluid (**?**).

Leakage practitioners often rewrite the equation in a more general form in order to apply it to leaks in pipes:

$$Q = Ch^{\alpha} \tag{5.2}$$

Where C is defined as the leakage coefficient, h is the pressure head, and α is the leakage exponent. α is sometimes referred to as N_1.

α is equal to 0.5 for an orifice with fixed area. However, the results of pressure management field studies have shown that the value of the leakage exponent often differs from this value. This means that a leak is much more sensitive to pressure than what was believed in the past. In 2007, van Zyl and Clayton proposed five factors that may be responsible for the high sensitivity of leakage to pressure: leak hydraulics, pipe material behavior, soil hydraulics, water demand, and the combined effect of many leaks.

Orifice hydraulics is well understood, and therefore it was long believed that the leakage exponent should be equal to 0.5. However, this is only true for turbulent flow (large Reynolds numbers). For laminar flow, the leakage coefficient is often written as a function of the Reynolds number. The relationship between the flow rate and pressure becomes linear. This means that the leakage coefficient can be as high as 1. However, laminar flow rarely exists in WDN.

Pipe material is also important in the understanding of the leakage exponent. The water pressure within a pipe is taken up by stresses in the pipe wall. It is suggested that plastic pipes exhibit higher α values because of their propensity to have longitudinal splits. Rigid pipes such as those comprised of metal are generally characterized by lower values of α (Giustolisi et al., 2008).

In 1996, the FAVAD concept was introduced. The assumption was that some leaks are rigid, while others will expand with increasing pressure. This assumption was later confirmed in a finite element study on the behavior of holes and cracks in pipes found that under elastic conditions (Cassa et al., 2010). The relationship can be written as:

$$A = A_0 + mh \tag{5.3}$$

WhereA_0 is the un-deformed leakage area under zero pressure, m is the slope of the linear law which links the leak area to the pressure head, and h is the pressure head. By replacing the area factor in Toricelli's equation with this new expression, we obtain the following relationship:

$$Q = C_d \left(A_0 + mh) \sqrt{2gh} \right) = C_d \sqrt{2g} \left(A_0 h^{0.5} + mh^{1.5} \right) \tag{5.4}$$

Which is known as the FAVAD equation. This equation shows that Toricelli's equation can still be used to represent the link between the discharge from a leak and pressure in a cracked pipe made of elastic material, as long as a correction is made to take account of the leak area (Franchini and Lanza, 2014).

According to Darcy's law and geotechnical seepage theory, the flow rate should be linearly proportional to the head of the water in the pipe if the head losses through the orifice are neglected. However, this is not necessarily the case for seepage around a water pipe. Since soils are not generally able to handle the pressure from leaks in water distribution pipes, it is unlikely that the impact of soils on the pressure-response of leakage is of significant importance.

Even though water demand is not classified as leakage, it can affect the leakage exponent. The reason is that it is often impossible to differ leakage from legitimate consumption. Therefore, leakage exponents in systems with demand are likely to be underestimated.

The research of van Zyl also suggests that the leakage exponent and the other parameters in the FAVAD equation are strongly related to the sum of all individual leak areas and head-area slopes in the system (Schwaller and van Zyl, 2014). The leakage exponent is discussed more in detail under section 6.2.6 in chapter 6.

Wagner et al. equation

In the late 1980s, it was argued that the nodal discharge in a water network model should not be considered constant. It should be related to the actual available nodal pressure. Wagner et al. proposed an equation that introduced a relationship between nodal pressure and nodal discharge. The actual quantity supplied in the system is dependent on the pressure at a node, and two pressure limits are given: (1) A minimum pressure P_j^{req}; and (2) a service pressure P_j^{min}. The system is defined to perform normally only when the imposed demands can be met with pressure above the service limit at each node. If the pressure is below the service limit at some node in the system, it is assumed that the system cannot supply the full demand at that node. The actual withdrawals will then be as follows (Wagner et al., 1988):

1. Nodes with pressure below the minimum pressure will be completely shut off.
2. Nodes with pressure above the minimum pressure but below the service pressure will be supplied at a reduced level.
3. Nodes with pressure above the service pressure will be fully supplied.

These withdrawals are continuous, with upper and lower bounds consistent with water distribution networks real behavior. The relationship can be written as a simple equation capable of modeling the true state of the network (Tabesh et al., 2014; Wagner et al., 1988):

$$Q_j^{avl} = \begin{cases} Q_j^{req}, & P_j > P_j^{req} \\ Q_j^{req} \left(\dfrac{P_j - P_j^{min}}{P_j^{req} - P_j^{min}} \right)^{\dfrac{1}{n}}, & P_j^{min} < P_j \leqslant P_j^{req} \\ 0, & P_j \leqslant P_j^{min} \end{cases} \tag{5.5}$$

in which Q_j^{req} is the demand required at node j; Q_j^{avl} is the available discharge at node j; P_j is the available pressure at node j; P_j^{req} is the minimum required pressure (demands and required discharges are supplied completely for pressures higher than this); P_j^{min} is the minimum pressure (discharge is zero for pressure levels lower than this); and n is the pressure exponent.

With this equation, each node can be in normal, reduced service, or failure mode. Normal mode means that all nodes are receiving normal supply; failure mode means that supply to any node has been shut off; and reduced mode means that some node or nodes are receiving reduced supply but no nodes are completely shut off.

The Wagner et al. equation is only able to determine the nodal discharge when the nodal pressure is between the minimum, P_j^{min}, and the minimum required pressure, P_j^{req}. This means that the equation fails to establish a relationship between nodal pressure and nodal demand for situations where the pressure level is greater than the minimum required pressure.

Wu et al. presented a modified version of the function in order to deal with this deficiency (Tabesh et al., 2014; Wu et al., 2009b):

$$Q_j^{avl} = \begin{cases} 0, & P_j \leqslant 0 \\ Q_j^{req}\left(\dfrac{P_j}{P_j^{des}}\right)^{\alpha}, & P_j \leqslant P^{thres} \\ Q_j^{req}\left(\dfrac{P^{thres}}{P_j^{des}}\right)^{\alpha}, & P_j \geqslant P^{thres} \end{cases} \tag{5.6}$$

where P_j is the calculated available pressure at node j; P_j^{des} is the desired or minimum required pressure at node j; P^{thres} is the threshold pressure (nodal discharge is independent of the nodal pressure for values greater than this); and α is an exponent of the pressure-demand relationship.

A new parameter, P^{thres}, is introduced in this function. When nodal pressure drops to and below zero, the demand is zero depending on the elevation of the customer taps relative to the node elevation. Pressure-dependent demand increases as nodal pressure increases, they are proportional. When nodal pressure reaches the desired or minimum required pressure level, P_j^{des}, the nodal demand is fully supplied. Nodal demand may keep increasing as the pressure is above the desired or minimum pressure level, but when the nodal pressure reaches the threshold, the nodal discharge does not increase anymore and remains constant. This means that demand is no longer sensitive to pressure. The pressure threshold must be greater than or equal to the minimum or required pressure level at which the target demand is met. This type of threshold exists for most types of demand except for leakage, which continuously increase with pressure (Wu et al., 2009b).

Chapter 6

WDNetXL

6.1 Introduction

The WDNetXL model is an integrated system for water distribution network analysis, planning and management distributed as MS-Excel add-ins (Laucelli et al., 2015). All analysis in the model shares the same platform HNSM, which can perform both DDA and PDA. The PDA of this model is based on an approach integrated by a pressure-driven background leakage model (Giustolisi et al., 2008). The ability to perform PDA makes the model state-of-the-art.

6.2 Modules

WDNetXL is equipped with different modules. The model has been applied to a case study and the observed convergence/error statistics has shown that the simulation model is robust (Berardi et al., 2015; Giustolisi et al., 2008).

6.2.1 Analysis

The *analysis module* consists of several functions that are based on hydraulic and topological analysis. There are six different functions that seeks to analyse the hydraulics of WDNs:

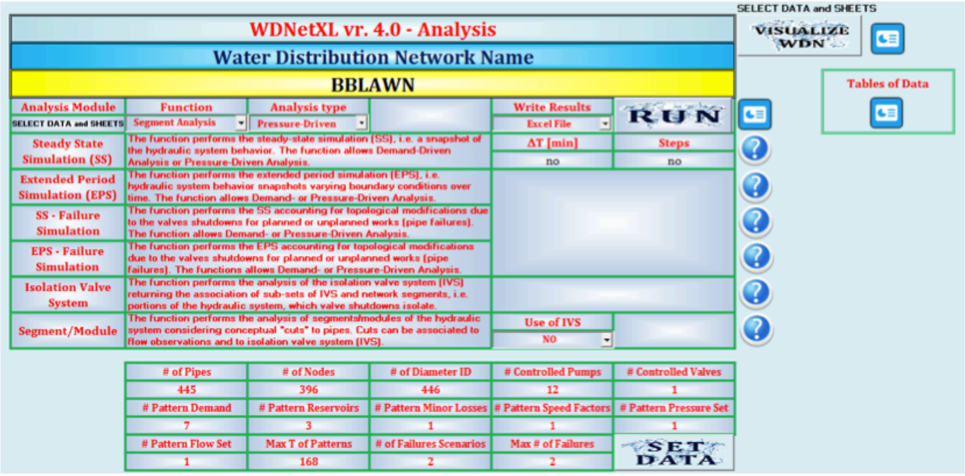
- **Steady State Simulation**: Performs a steady state simulation (SSS) of the WDS, i.e. a snapshot of the hydraulic system behaviour. The function allows both DDA or PDA.
- **Extended Period Simulation**: Performs an extended period simulation (EPS) of the WDS, i.e. s sequence of snapshots of the hydraulic system behaviour with varying boundary conditions over time. The function allows both DDA or PDA.

- **Steady State Failure Simulation**: Performs a SSS accounting for topological modifications due to shutdown of valves for planned or unplanned (i.e. pipe failures) events. The function allows both DDA or PDA.

- **Extended Period Failure Simulation**: Performs a EPS accounting for topological modifications due to shutdown of valves for planned or unplanned (i.e. pipe failures) events. The function allows both DDA or PDA.

- **Isolation Valve System (IVS)**: Performs an analysis of the isolation valve system (IVS) returning the association of sub-sets of IVS and network segments, i.e. areas in the systems that valve shutdowns isolate.

- **Segment/Module**: Performs an analysis of segments/modules of the hydraulic system considering conceptual cuts that conceptually divide the WDN into segments/districts. The cuts can be associated to flow observations and to the IVS.



WDNetXL vr. 4.0 - Analysis

Water Distribution Network Name

BBLAWN

Analysis Module: SELECT DATA and SHEETS

Function: Segment Analysis

Analysis type: Pressure-Driven

Write Results: Excel File

ΔT [min]: no

Steps: no

Use of IVS: NO

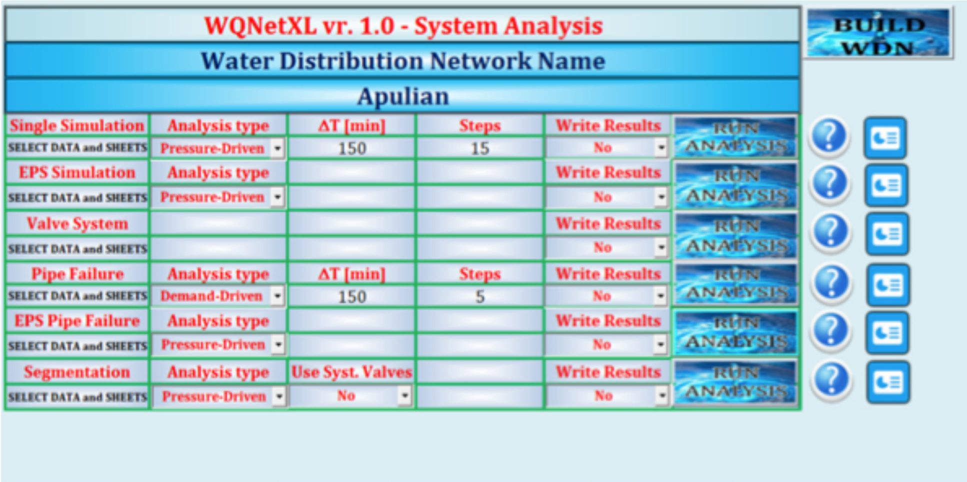
Steady State Simulation (SS)	The function performs the steady-state simulation (SS), i.e. a snapshot of the hydraulic system behavior. The function allows Demand-Driven Analysis or Pressure-Driven Analysis.
Extended Period Simulation (EPS)	The function performs the extended period simulation (EPS), i.e. hydraulic system behavior snapshots varying boundary conditions over time. The function allows Demand- or Pressure-Driven Analysis.
SS - Failure Simulation	The function performs the SS accounting for topological modifications due to the valves shutdowns for planned or unplanned works (pipe failures). The function allows Demand- or Pressure-Driven Analysis.
EPS - Failure Simulation	The function performs the EPS accounting for topological modifications due to the valves shutdowns for planned or unplanned works (pipe failures). The functions allows Demand- or Pressure-Driven Analysis.
Isolation Valve System	The function performs the analysis of the isolation valve system (IVS) returning the association of sub-sets of IVS and network segments, i.e. portions of the hydraulic system, which valve shutdowns isolate.
Segment/Module	The function performs the analysis of segmentsfmodules of the hydraulic system considering conceptual "cuts" to pipes. Cuts can be associated to flow observations and to isolation valve system (IVS).

# of Pipes	# of Nodes	# of Diameter ID	# Controlled Pumps	# Controlled Valves
445	396	446	12	1
# Pattern Demand	# Pattern Reservoirs	# Pattern Minor Losses	# Pattern Speed Factors	# Pattern Pressure Set
7	3	1	1	1
# Pattern Flow Set	Max T of Patterns	# of Failures Scenarios	Max # of Failures	
1	168	2	2	

Figure 6.1: User interface of WDNetXL Analysis Module (hydroinformatics.it, 2016).

6.2.2 Water quality

WQNetXL is a separate model that has a lot of similarities with WDNetXL. It is collection of MS-Excel add.ins, and is classified as a system tool for water quality analyses of WDNs. The analyses are based on network hydraulics and kinetics of travelling substances, i.e. background leakages (see 6.2.6) and pressure deficient conditions (see chapter 5) (Berardi et al., 2014).



WQNetXL vr. 1.0 - System Analysis

Water Distribution Network Name

Apulian

Single Simulation	Analysis type	ΔT [min]	Steps	Write Results	RUN ANALYSIS
SELECT DATA and SHEETS	Pressure-Driven	150	15	No	
EPS Simulation	Analysis type			Write Results	RUN ANALYSIS
SELECT DATA and SHEETS	Pressure-Driven			No	
Valve System				Write Results	RUN ANALYSIS
SELECT DATA and SHEETS				No	
Pipe Failure	Analysis type	ΔT [min]	Steps	Write Results	RUN ANALYSIS
SELECT DATA and SHEETS	Demand-Driven	150	5	No	
EPS Pipe Failure	Analysis type			Write Results	RUN ANALYSIS
SELECT DATA and SHEETS	Pressure-Driven			No	
Segmentation	Analysis type	Use Syst. Valves		Write Results	RUN ANALYSIS
SELECT DATA and SHEETS	Pressure-Driven	No		No	

Figure 6.2: User interface of WQNetXL Hydraulic and Topological System Analysis *(hydroinformatics.it, 2016)*.

Figure 6.3: User interface of WQNetXL Steady-State Water Quality Analysis and Steady-State Water Quality Failure Analysis (hydroinformatics.it, 2016).

6.2.3 Design

The *design module* consists of several functions that are based on hydraulic and topological analysis. There are seven different functions that seeks to perform optimal designs for WDNs:

- **Hydraulic Capacity Design**: Performs a design analysis to acquire the optimal sizing of pipes and/or pumps in the network. This is based on an multi-objective optimization strategy that also takes into account valve shut-downs. The function allows both DDA or PDA.

- **Isolation Valve System Design**: Performs a design analysis to acquire the optimal design of the IVS in the network, by using a multi-objective optimization algorithm strategy. The decision variables of the algorithm are the location of isolation valves close to nodes.

- **Pressure Sampling Design**: Performs a design analysis to acquire a nodal pressure sampling in the network, by using a multi-objective optimization algorithm strategy. The decision variables of the algorithm are the location pressure meters within the network.

- **Segmentation Design**: Performs a design analysis to acquire a optimal design of the segments/modules in the network. This is done by using a multi-objective optimization algorithm strategy, a WDN-oriented infrastructure or the classic modularity index.

- **District Metering Areas Design**: Performs a design analysis to acquire the optimal division district metered areas (DMAs) in the network, by using a multi-objective optimization algorithm strategy. It also takes use of an optimal segmentation design function. The decision variables pipes to be closed to create a division in the network.

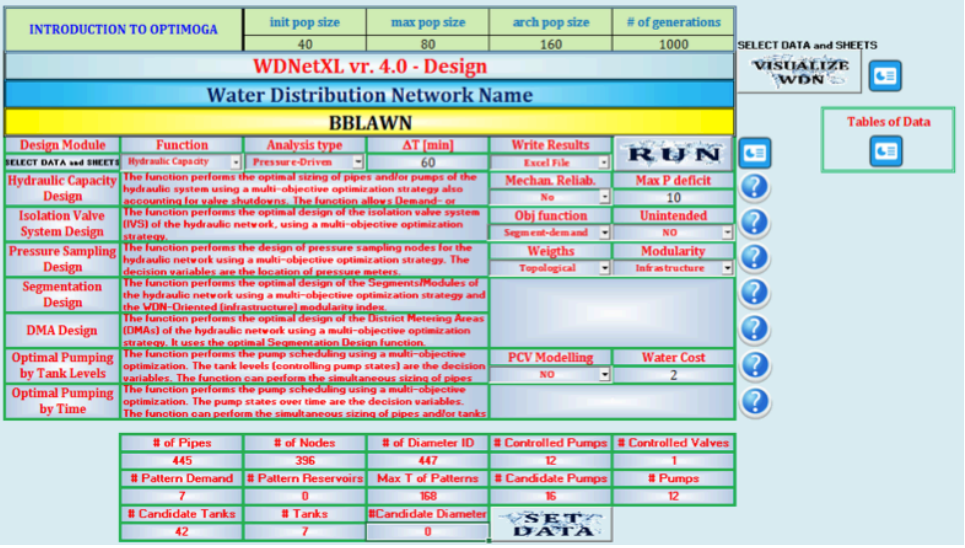
- **Optimal Pumping by Tank Levels**: Performs an optimization of the pumping schedule by using a multi-objective optimization algorithm (MOGA). The decision variables in the algorithm are the tank levels. The function can perform a simultaneous optimization of pipe/tank sizing using both DDA or PDA.

- **Optimal Pumping by Time**: Performs an optimization of the pumping schedule by using a multi-objective optimization algorithm (MOGA). The decision variables in the algorithm are the states of a pump over time. The function can perform a simultaneous optimization of pipe/tank sizing using both DDA or PDA.

6.2.4 Management

The *management module* consists of several functions that are based on hydraulic and topological analysis. There are five different functions that seeks to analyse and optimize different assets within the WDN:

- **Reliability One Failure**: Performs a mechanical reliability analysis of the network by assuming one mechanical failure at a time. These failures could be nodal failure, pipe failure, valve shutdowns etc. The function can be ran with DDA or PDA.



INTRODUCTION TO OPTIMOGA	init pop size	max pop size	arch pop size	# of generations
	40	80	160	1000

WDNetXL vr. 4.0 - Design

Water Distribution Network Name

BBLAWN

Design Module	Function	Analysis type	ΔT [min]	Write Results	
SELECT DATA and SHEETS	Hydraulic Capacity	Pressure-Driven	60	Excel File	RUN

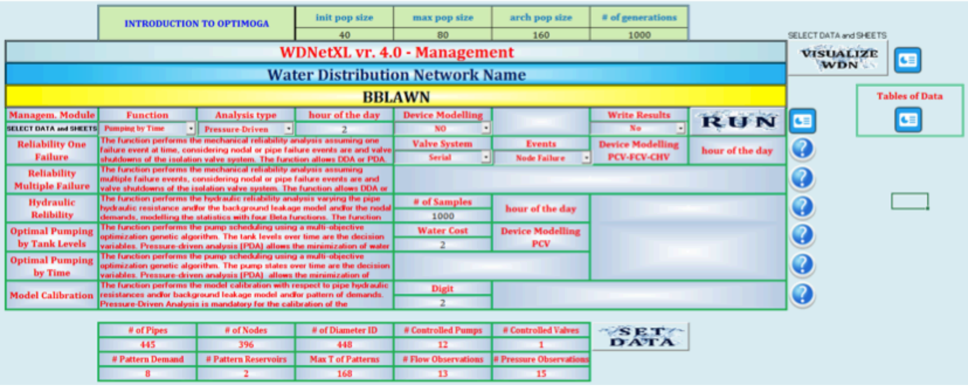
Hydraulic Capacity Design	The function performs the optimal sizing of pipes and/or pumps of the hydraulic system using a multi-objective optimization strategy also accounting for valve shutdowns. The function allows Demand- or	Mechan. Reliab. No	Max P deficit 10
Isolation Valve System Design	The function performs the optimal design of the isolation valve system (IVS) of the hydraulic network, using a multi-objective optimization strategy.	Obj function Segment-demand	Unintended NO
Pressure Sampling Design	The function performs the design of pressure sampling nodes for the hydraulic network using a multi-objective optimization strategy. The decision variables are the location of pressure meters.	Weigths Topological	Modularity Infrastructure
Segmentation Design	The function performs the optimal design of the Segments/Modules of the hydraulic network using a multi-objective optimization strategy and the WDN-Oriented (infrastructure) modularity index.		
DMA Design	The function performs the optimal design of the District Metering Areas (DMAs) of the hydraulic network using a multi-objective optimization strategy. It uses the optimal Segmentation Design function.		
Optimal Pumping by Tank Levels	The function performs the pump scheduling using a multi-objective optimization. The tank levels (controlling pump states) are the decision variables. The function can perform the simultaneous sizing of pipes	PCV Modelling NO	Water Cost 2
Optimal Pumping by Time	The function performs the pump scheduling using a multi-objective optimization. The pump states over time are the decision variables. The function can perform the simultaneous sizing of pipes and/or tanks		

# of Pipes	# of Nodes	# of Diameter ID	# Controlled Pumps	# Controlled Valves
445	396	447	12	1
# Pattern Demand	# Pattern Reservoirs	Max T of Patterns	# Candidate Pumps	# Pumps
7	0	168	16	12
# Candidate Tanks	# Tanks	#Candidate Diameter		
42	7	0		

Figure 6.4: User interface of WDNetXL Design Module (hydroinformatics.it, 2016).

- **Reliability Multiple Failures**: Performs a mechanical reliability analysis of the network by assuming multiple failure events at the same time. These failures could be nodal failure, pipe failure, valve shutdowns etc. The function can be ran with DDA or PDA.
- **Hydraulic Reliability**: Performs a hydraulic reliability analysis of the network by varying different uncertain parameters in the network. These could be varied by themselves alone or in combination with each other. The parameters are the hydraulic resistance of the pipes in the network, the background leakage parameters, and the nodal demands. The function models the statistics with four $\beta - functions$ and allows for both DDA or PDA
- **Optimal Pumping by Tank Levels**: Performs an optimization of the pumping schedule by using a multi-objective optimization algorithm (MOGA). The decision variables in the algorithm are the tank levels. Takes use of PDA to minimize the water loss.
- **Optimal Pumping by Time**: Performs an optimization of the pumping schedule by using a multi-objective optimization algorithm (MOGA). The decision variables in the algorithm are the states of a pump over time. Takes use of PDA to minimize the water loss.
- **Model Calibration**: Performs a model calibration by varying different uncertain parameters in the network. These could be varied by themselves alone or

in combination with each other. The parameters are the hydraulic resistance of the pipes in the network, the background leakage parameters, and the nodal demands. This function has to take use of PDA in order for the background leakage model to be valid.



init pop size	max pop size	arch pop size	# of generations
40	80	160	1000

WDNetXL vr. 4.0 - Management

Water Distribution Network Name

BBLAWN

Managem. Module	Function	Analysis type	hour of the day	Device Modelling		Write Results
SELECT DATA and SHEETS	Pumping by Time	Pressure-Driven	2	NO		No

Module	Description
Reliability One Failure	The function performs the mechanical reliability analysis assuming one failure event at time, considering nodal or pipe failure events are and valve shutdowns of the isolation valve system. The function allows DDA or PDA.
Reliability Multiple Failure	The function performs the mechanical reliability analysis assuming multiple failure events, considering nodal or pipe failure events are and valve shutdowns of the isolation valve system. The function allows DDA or
Hydraulic Relibility	The function performs the hydraulic reliability analysis varying the pipe hydraulic resistance and/or the background leakage model and/or the nodal demands, modelling the statistics with four Beta functions. The function
Optimal Pumping by Tank Levels	The function performs the pump scheduling using a multi-objective optimization genetic algorithm. The tank levels over time are the decision variables. Pressure-driven analysis (PDA) allows the minimization of water
Optimal Pumping by Time	The function performs the pump scheduling using a multi-objective optimization genetic algorithm. The pump states over time are the decision variables. Pressure-driven analysis (PDA) allows the minimization of
Model Calibration	The function performs the model calibration with respect to pipe hydraulic resistances and/or background leakage model and/or pattern of demands. Pressure-Driven Analysis is mandatory for the calibration of the

Valve System: Serial
Events: Node Failure
Device Modelling PCV-FCV-CHV
hour of the day
# of Samples: 1000
hour of the day
Water Cost: 2
Device Modelling PCV
Digit: 2

# of Pipes	# of Nodes	# of Diameter ID	# Controlled Pumps	# Controlled Valves
445	396	448	12	1
# Pattern Demand	# Pattern Reservoirs	Max T of Patterns	# Flow Observations	# Pressure Observations
8	2	168	13	15

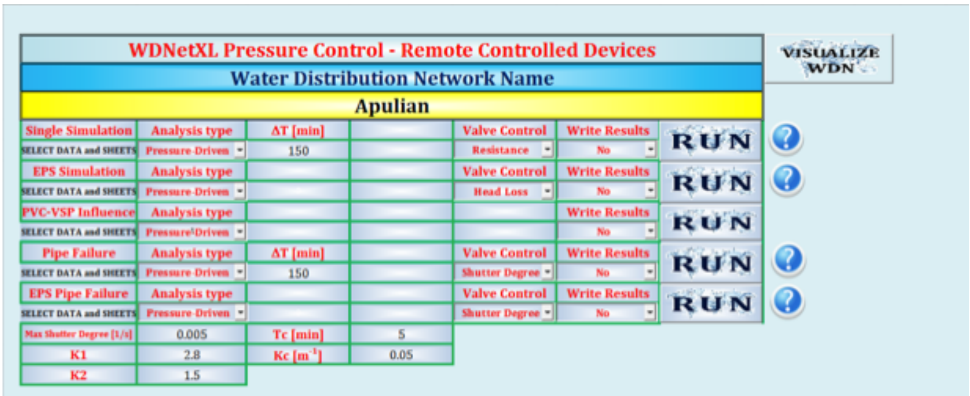
Figure 6.5: User interface of WDNetXL Management Module *(hydroinformatics.it, 2016).*

6.2.5 Pressure control

The *pressure control module* supports the planning and real-time functioning analysis of RRTC devices. It contains functions to perform the same standard hydraulic and topological analyses as the other modules of WDNetXL. The functions use PDA and considers background leakages (see 6.2.6), different components of demand (residential, industry etc.), and failure events (e.g. valve shutdowns) in order to set and run the RRTC modeling functions. The standard analysis functions allow to model any remote unit device and in particular RRTC pressure control valves (PCVs) and variable speed pumpss (VSPs) (Giustolisi et al., 2015).

6.2.6 Leakage control

One of the most important features of the WDNetXl model is the possibility to perform pressure-driven analysis. The *leakage module* includes both the simulation of background leakages and the definition of several components in each node. Background leakages are modeled at node level (simulating pipe bursts dependent on nodal pressure) and at pipe level (background leakage dependent on average pressure along the pipes). Because these are separated, it is possible to simulate effects of pressure management on different components, making WDNetXL a powerful tool for leakage management (Laucelli et al., 2015).



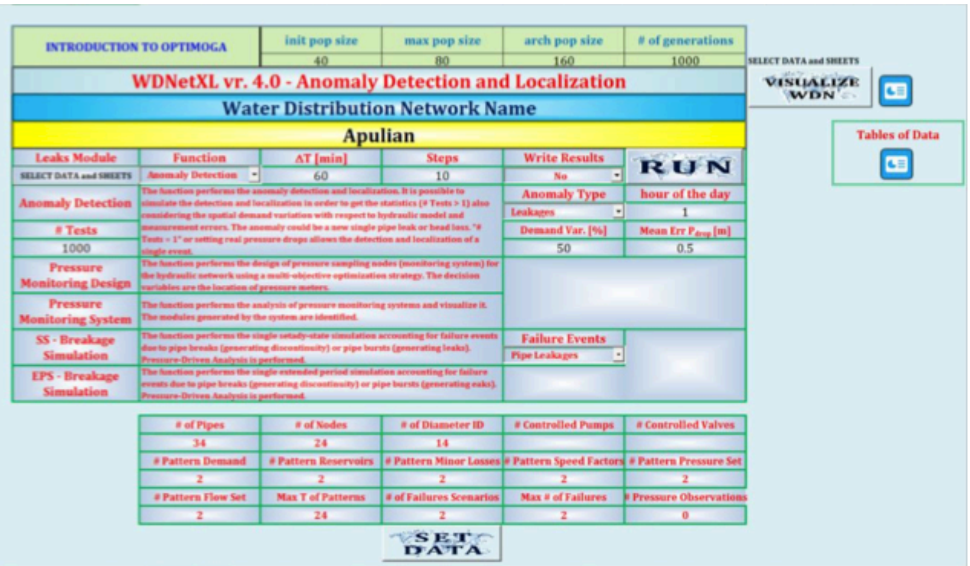
WDNetXL Pressure Control - Remote Controlled Devices

Water Distribution Network Name

Apulian

Single Simulation	Analysis type	ΔT [min]		Valve Control	Write Results
SELECT DATA and SHEETS	Pressure-Driven	150		Resistance	No
EPS Simulation	Analysis type			Valve Control	Write Results
SELECT DATA and SHEETS	Pressure-Driven			Head Loss	No
PVC-VSP Influence	Analysis type				Write Results
SELECT DATA and SHEETS	Pressure-Driven				No
Pipe Failure	Analysis type	ΔT [min]		Valve Control	Write Results
SELECT DATA and SHEETS	Pressure-Driven	150		Shutter Degree	No
EPS Pipe Failure	Analysis type			Valve Control	Write Results
SELECT DATA and SHEETS	Pressure-Driven			Shutter Degree	No
Max Shutter Degree [1/s]	0.005	Tc [min]	5		
K1	2.8	Kc [m^{-1}]	0.05		
K2	1.5				

Figure 6.6: User interface of WDNetXL Pressure Control Module (hydroinformatics.it, 2016).



INTRODUCTION TO OPTIMOGA	init pop size	max pop size	arch pop size	# of generations
	40	80	160	1000

SELECT DATA and SHEETS

WDNetXL vr. 4.0 - Anomaly Detection and Localization

Water Distribution Network Name

Apulian

Leaks Module	Function	ΔT [min]	Steps	Write Results
SELECT DATA and SHEETS	Anomaly Detection	60	10	No

Anomaly Detection # Tests 1000	The function performs the anomaly detection and localization. It is possible to simulate the detection and localization in order to get the statistics (# Tests > 1) also considering the spatial demand variation with respect to hydraulic model and measurement errors. The anomaly could be a new single pipe leak or head loss. "# Tests = 1" or setting real pressure drops allows the detection and localization of a single event.	Anomaly Type Leakages Demand Var. [%] 50	hour of the day 1 Mean Err P_{drop} [m] 0.5
Pressure Monitoring Design	The function performs the design of pressure sampling nodes (monitoring system) for the hydraulic network using a multi-objective optimization strategy. The decision variables are the location of pressure meters.		
Pressure Monitoring System	The function performs the analysis of pressure monitoring systems and visualize it. The modules generated by the system are identified.		
SS - Breakage Simulation	The function performs the single setady-state simulation accounting for failure events due to pipe breaks (generating discontinuity) or pipe bursts (generating leaks). Pressure-Driven Analysis is performed.	Failure Events Pipe Leakages	
EPS - Breakage Simulation	The function performs the single extended period simulation accounting for failure events due to pipe breaks (generating discontinuity) or pipe bursts (generating eaks). Pressure-Driven Analysis is performed.		

# of Pipes	# of Nodes	# of Diameter ID	# Controlled Pumps	# Controlled Valves
34	24	14		
# Pattern Demand	# Pattern Reservoirs	# Pattern Minor Losses	# Pattern Speed Factors	# Pattern Pressure Set
2	2	2	2	2
# Pattern Flow Set	Max T of Patterns	# of Failures Scenarios	Max # of Failures	# Pressure Observations
2	24	2	2	0

Figure 6.7: User interface of WDNetXL Leakage Control Module (hydroinformatics.it, 2016).

Background leakage

Nodal demands are modeled in WDNetXL according to the FAVAD concept and Wagner et al. (1988) equation. The Wagner et al. (1988) equation is also the basis for modeling background leakages at a node level. At a pipe level, WDNetXL takes use of a model proposed by Germanopoulos (1985). The outflow along the kth pipe is a function of the average pipe pressure:

$$q_k^{leak} = \beta_k l_k \left(\frac{P_i + P_j}{2} \right)^{\alpha_k} = \beta_k l_k (P_{k,mean})^{\alpha_k} \tag{6.1}$$

where q_k^{leak} is the outflow on a pipe-level; l_k is the length of the pipe; $P_{k,mean}$ is the average pressure along the pipe between node i and j; α_k and $beta_k$ are leakage model parameters that has to be determined through calibration (explained and discussed later). As presented in Giustolisi et al. (2008) the index k is used for pipe-level variables and the index i is used for nodal-level variables. By assuming a uniform distribution along the pipe, the background leakage can be expressed as:

$$q_k^{leak} = \begin{cases} \beta_k l_k (P_{k,mean})^{\alpha_k}, & P_k > 0 \\ 0, & P_k \leqslant 0 \end{cases} \tag{6.2}$$

The nodal leakage flow, q_i^{leak}, can be expressed as the sum of q_k^{leak} flows of all pipes connected to node i. The allocation of leakage to two end nodes along a pipe can be performed in several ways. The simplest approach is to assume that half of the leakage from the pipe element occurs at each of the end nodes:

$$q_i^{leak} = \sum_k \frac{1}{2} q_k^{leak} = \sum_k \frac{1}{2} \beta_k l_k (P_{k,mean})^{\alpha_k} \tag{6.3}$$

The more realistic approach is to divide the total leakage in proportion in with the magnitude of the two nodal pressures, Pi and Pj:

$$q_i^{leak} = \sum_k \frac{P_i}{P_i + P_j} q_k^{leak} = \frac{P_i}{2} \sum_k \beta_k l_k (P_k)^{\alpha_k - 1} \tag{6.4}$$

where

$$P_k = \frac{P_i + P_j}{2}$$

The pressure-leakage relationship is defined in a column vector, $\mathbf{q_l}$, whose elements are nodal leakages (that is computed from the pipe leakage model). Background leakage is only one demand component in the total water distribution model, and the WDNetXL model assumes that the pipe outflows are lumped at ending nodes. The relationship used in the model is computed from a topological (network incidence) matrix :

$$\mathbf{q_l} = \frac{1}{2}\left|\mathbf{A_{np}}\right| \begin{bmatrix} q_l^{leak} \\ K \\ q_k^{leak} \\ K \\ q_{np}^{leak} \end{bmatrix} \tag{6.5}$$

where $|\mathbf{A_{np}}|$ is the absolute value of the matrix; and the $\mathbf{q_l}$ elements are from the matrix product involving the topological matrix $\mathbf{A_{np}}$.

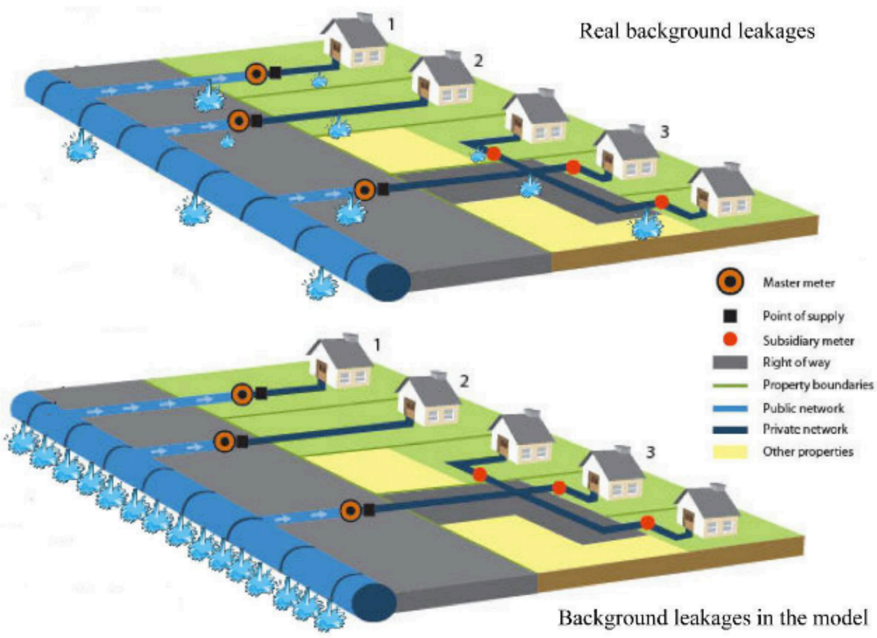


Figure 6.8: Background leakage representation in WDNetXL: the real background leakages (upper) in the WDN is represented as uniformly distributed background leakages along the pipes in the WDN model, according to the Germanopoulus formulation (Laucelli et al., 2015).

Model parameters

α_k and β_k are parameters that should be estimated for each pipe in the model. There is a broad consensus among researchers today that α_k depends on the balance between burst ($\alpha_k = 0.5$) and background leakage flows ($\alpha_k > 0.5$) and can be determined by means of model calibration or component analysis (Giustolisi et al., 2008). It is a function of pipe characteristics only. Berardi et al. (2015) suggest that the α_k exponent can be assumed a priori based on pipe material and, considering possible uncertainties surrounding local outflow conditions, it can be realistically assumed to be the same over the entire network. Several values have been suggested over the years. For example, Jowitt and Xu (1990) and Vairavamoorthy and Lumbers (1998) obtained the value of $\alpha_k = 1.18$ from field data. Later, Lambert (2001) found values ranging from $\alpha_k = 0.5 - 2.50$ depending on the mixture of leaks and the dominant type of leaks. In general, plastic pipes have higher α_k values because of their propensity to have longitudinal splits. Rigid pipes generally have lower α_k values. However, Lambert reported α_k values of around 1.5 regardless of the pipe material. In recent times, Maskit and Ostfeld (2014) reported α_k values ranging from 0.9-1.3 from a Genetic algorithm (GA) calibration.

β_k depends on both pipe characteristics and various external factors that may contribute to the likelihood of failure. From a hydraulic standpoint, β_k can be considered as the background leakage outflow running from a unit length of pipe under unit mean pressure (Berardi et al., 2015). Since the rate of system deterioration is influenced by pressure management (Lambert, 2001), β_k exponentially increases at a rate whose coefficient is dependent on the pressure regime in the system. β_k also depend on pipe conditions, and for this reason, its range of variation is wider than that of α_k. Therefore, β_k has to be decided through model calibration in order to minimize the discrepancy between model predictions and field observations.

Finally, β_k is more closely related to the number of leaks (or leakage area) per unit of pipe length while α_k is more strongly related to the type of leakage (therefore to the hydraulics of leakage) as governed by pipe material (Giustolisi et al., 2008; Lambert, 2001).

6.3 E^3-network WDN as implemented in WDNetXL

All data used to create the E^3-network model was provided by VAV as an EPANET*.inp file which contained anonymized data of the system. The main features of the model are taken from the report "Hydraulic model of E3network water distribution network in WDNetXL", written by the IDEA-RT team, and summarized in this section:

The model consists of:

- 5440 nodes with elevations between sea level and 230 meter a.s.l. The topography in the network area make the system highly dependent on sufficient pressure control from pumping stations and pressure reduction valves to ensure a stable service pressure.
- 5 reservoirs and one variable level tank.
- 5812 pipes, 108 of them closed.
- 16 pumps divided into 5 pumping stations. Three stations were set as "open", and two were "closed".
- Three VSPs which were located in three different pumping stations.
- 44 PCVs, where 17 were "closed".
- One check valve.
- Gate valves are assumed to be located next to all pressure tanks, reservoirs, and control devices.
- 13 demand patterns to represent nodal demands. Leakage patterns are not used as the background leakages are simulated as pressure-dependent demand components.

Chapter 7

Refining the WDNetXL model

7.1 Introduction

One of the objectives of this thesis is to refine the existing model of the E^3-network. The data was suppose to be used in the management module in order to calibrate the model with flow and pressure values from actual measurements. However, the management module could not be used as it was not functioning at the time this thesis was written. Therefore, the data was used to create new demand patterns and to refine the β-value set by the developers of the model. This was done in the analysis module and considered to be the best way of using the data in this thesis.

7.2 Input data requirements

All data in the E^3-network HNSM is imported from an EPANET file provided by VAV. Information needed to run the model includes pipe roughness coefficient, pipe diameter, pump characteristics etc. However, discrete time series of actual flow and pressure for all measuring points in the system was the only data required for the purpose of this thesis.

7.3 Refining the model with new demand patterns

The WDS of E^3WDM consists of approximately 5812 pipes and 5440 nodes, which includes 40 measurement points distributed in 13 different DMAs. These points (nodes) are equipped with sensors and meters that measure various physical quantities. Almost all the points measure pressure and flow. Data from all 40 points had to be retrieved in order to refine the existing HNSM of the E^3-network. The DMAs are defined by the developers of the E^3-network HNSM. A demand pattern is defined for every DMA , as shown in Table 7.1 (Giustolisi et al., 2016).

Pattern ID	DMA	# of nodes
1	7DGOLMH	2029
2	7F	676
3	7J	182
4	7K	98
5	7N	185
6	7P	175
7	7Q	29
8	7R	108
9	7V	6
10	MK107	1
11	RK155	1
12	RK156	1
13	RK159	1

Table 7.1: DMAs as defined by the model developers at IDEA-RT (Giustolisi et al., 2016).

7.3.1 Data resolution and treatment

Raw data was retrieved to avoid that any invalid calculations were performed in the process (see subsection 8.3.1). The data was then averaged using simple mathematics, as described in subsection 4.3.6, to create an evenly spaced discrete time series.

It was important to handle the "bad" loggings in a good way, so that they would not be counted as zeros in the calculation. "Bad" loggings were treated in three different ways:

1. If one "bad" logging occurred in between two good loggings, the "bad" reading was erased from the sample set. This was considered to be valid since the meters/sensors logged data in high resolution and the amount of good quality data was significant in all sample sets.
2. If two "bad" loggings occurred in between two good loggings, the "bad" loggings were simply replaced with interpolated values from the good loggings. This was considered to be valid since the logging most likely would not vary too much from the neighbouring good loggings.
3. If more than two "bad" loggings occurred in between two good loggings, the data set was considered to be invalid, and the hourly average would just be marked as "bad".

One month of raw data was retrieved from the historian database for every measuring point. These data was then examined and averaged into hourly intervals. The goal was to find a week with daily good quality data sample series (24 values with measurements starting at 00:00:01 and ending at 23:59:59 on the same day), meaning series where no hourly interval had to be marked as "bad". A great effort was made to achieve this. Good quality data series were retrieved from 11 of the 13 different DMAs, as two DMAs suffered from malfunctioning equipment which could not provide any good measurements at all.

7.3.2 Calculating new demand patterns

The good quality data series for 11 out of the 13 zones were used for model refinement. The pattern that was defined by the model developers were used in the zone were no good data could be retrieved. Sample sets from the 1st week of july 2015 was used for the remaining zones. An example of a sample set that was used from DMA zone MK107 is shown in Table 7.2. The table displays the set that was used to calculate demand factors for July 1st.

Tagname	VAV1.MK107_FT1_VERDI.F_CV
Description	Momentanverdi (F_CV)
Engineering Units	l/s

Timestamp	Value	Timestamp	Value
01-juli-15 01:00:00	102,1181831	01-juli-15 13:00:00	87,85353088
01-juli-15 02:00:00	100,4907651	01-juli-15 14:00:00	90,03056276
01-juli-15 03:00:00	97,11649397	01-juli-15 15:00:00	91,69876979
01-juli-15 04:00:00	80,88770905	01-juli-15 16:00:00	94,57326358
01-juli-15 05:00:00	74,61269363	01-juli-15 17:00:00	96,99363647
01-juli-15 06:00:00	70,70192857	01-juli-15 18:00:00	97,89222039
01-juli-15 07:00:00	68,3294889	01-juli-15 19:00:00	99,19457245
01-juli-15 08:00:00	67,64095532	01-juli-15 20:00:00	103,1820056
01-juli-15 09:00:00	69,50306405	01-juli-15 21:00:00	103,0288007
01-juli-15 10:00:00	75,69466697	01-juli-15 22:00:00	99,20672469
01-juli-15 11:00:00	80,33302811	01-juli-15 23:00:00	98,44862459
01-juli-15 12:00:00	83,93755059	02-juli-15 00:00:00	102,1781085

Table 7.2: 24hr sample serie for the MK107 DMA(Oslo Water and Sewerage Works (VAV), 2016).

Calculations

A series of calculations were carried out on the sample sets to create new demand patterns:

Firstly, the values within the data sets were averaged, using the standard formula for arithmetic average calculations:

$$A = \frac{1}{24}\sum_{i}^{24} a_i, \quad i \in \{1, 2, ..., 24\} \tag{7.1}$$

Where A is the arithmetic average, 24 is the number of measurements, and a_i is the value of a specific measurement. Then each value was divided by the arithmetic average:

$$f^{i}_{demand} = \frac{a_i}{A}, \quad i \in \{1, 2, ..., 24\} \tag{7.2}$$

Which equals the demand factor for the specific sample set. This was done for every sample set within each zone to create multiple sets of demand factors. Table 7.3 shows the demand factors for every measuring point that is located within the 7H DMA. The demand factors for the sample set should add up to 24 for every measuring point.

Further analysis included an analysis of variance (ANOVA) test. This test is used to determine if there are any significant differences between the means of three or more independent groups. An independent group means that it is unrelated to the other groups. Specifically, ANOVA tests the null hypothesis:

- **Null hypothesis**: $H_0 : \mu_0 = \mu_1 = \cdots = \mu_k$
  Where μ=group mean and k =number of groups.
- **Alternative hypothesis**: There are at least two group means that are significantly different from each other.

If the test returns a significant result, we accept the alternative hypothesis. A statistical significance is defined as whether or not the p-value is less than the significance level, α. The p-value is the probability of obtaining at least as extreme results given that the null hypothesis is true, whereas the significance level α is the

hr	RK132	RK135	RK136	RK137
1	0,820056954	0,531413395	0,816470214	1,041047285
2	0,691760947	0,338753124	0,680612095	1,003296211
3	0,660459483	0,436312422	0,647206689	0,937496205
4	0,66265042	0,573469454	0,623306584	0,842548325
5	0,671908845	0,702302512	0,615503719	0,7905932
6	0,705980004	0,797359871	0,686339852	0,794380832
7	0,957735544	0,948745948	0,872917742	0,887141667
8	1,042887239	1,064280254	1,043997928	0,968226866
9	1,055086381	1,038292048	1,046997451	0,989732371
10	1,01166425	1,047890086	1,064403691	1,007507477
11	0,926348899	0,995043483	1,026223141	0,989375454
12	0,944814035	1,005708935	1,015988378	0,97530261
13	0,942061382	0,979470858	1,008085396	0,974032887
14	0,924218265	1,068768374	1,022026796	0,983810811
15	0,923087716	1,085784722	1,008646273	0,997787053
16	1,02363847	1,120682592	1,039100694	0,997628934
17	1,159914436	1,273417989	1,166944028	1,046735281
18	1,269593738	1,292529278	1,258122984	1,091855917
19	1,354710546	1,401527952	1,258765964	1,146442631
20	1,275941745	1,297310438	1,26215497	1,131177845
21	1,363061748	1,406426285	1,291387422	1,123570413
22	1,330250704	1,393405943	1,277083142	1,116359582
23	1,246090262	1,259890454	1,214614073	1,09535301
24	1,036077988	0,941213582	1,053100774	1,068597133
	$Sum = 24$	$Sum = 24$	$Sum = 24$	$Sum = 24$

Table 7.3: f_{demand} for different measuring points within 7H, which is a sub-area of zone 7DGOLMH.

probability of rejecting the null hypothesis given that it is true. α is the threshold value which p-values are measured against.

There are three main assumptions that needs to be met in order for the test to be valid (Lærd Statistics, 2013):

1. The dependent variable is normally distributed. Normal distribution is used to represent real-valued random variables whose distributions are not known. Therefore, the flow measurements can be assumed to be normally distributed..

2. There is homogeneity of the variances. This means that the population variances in each group are similar or equal. This is assumed to be true for these kind of measurements.

3. Independence of observations. This means that there is no relationship between the observations in each group or between the groups themselves. Each flow measurement is independent and it is assumed that there are no relationship between the measurements in each measuring point. This holds since each measuring point measure flow independent of each other.

The significance level for the ANOVA test was set to $\alpha = 0.05$, which means that there is a 5% chance that the null hypothesis is rejected when it is actually true. All groups that had p-values which did not meet the significance level requirement were rejected. The final demand factors were constructed from the average of the groups that passed the ANOVA test. An example of a new demand pattern for the 7DGOLMH DMA is shown in Figure 7.1.

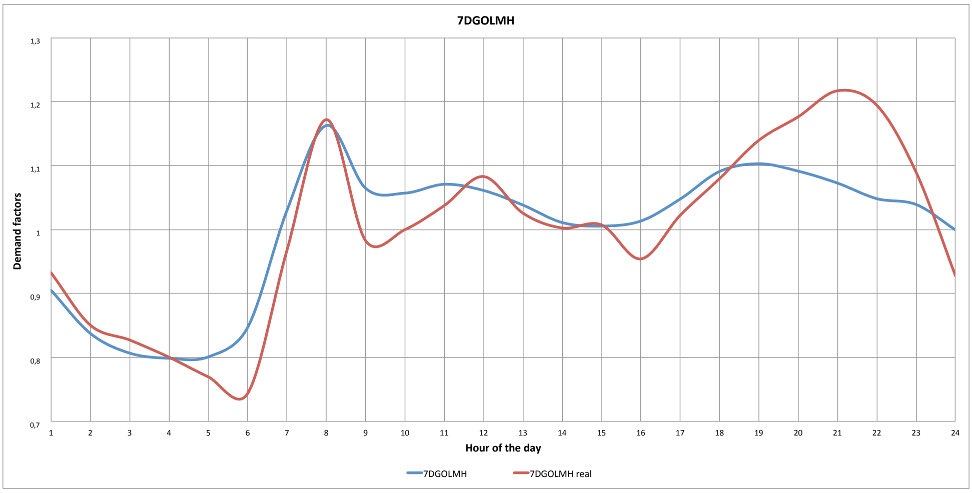


Figure 7.1: Demand pattern created from actual data (red line) vs. demand pattern provided by model developers (blue line).

7.3.3 Simulation with new demand patterns

All calculations were performed in excel to ensure compatibility with WDNetXL. There is an automated import function that is under development by the IDEA-RT team, but it is not available for commercial use yet. Therefore, the patterns were simply exported from the calculation spreadsheet and into the model.

The analysis module was used to run a simulation with the old and the new demand patterns. The results are presented in chapter 8.

7.4 Refinement of β

The values of β in the HNSM model of the E^3-network were obtained from the preliminary estimation of leakages at every node of the system, which was provided by VAV. These estimations are based on past water balance data and expected pressure regimes. They were originally provided as an additional component of nodal demand, which follows an hypothetic time pattern of leakage outflow that was assumed to be inversely proportional to the demand pattern for household consumption, i.e. minimum leakage outflow occurs at peak household demand and vice versa. New demand patterns will cause a change in the leakage outflow. Therefore, the β-values needs to be changed in order for the leakage percentage value to remain the same with the new demand patterns. The leak percentage used in the E^3-network model was also provided by VAV. This value is assumed to be accurate.

The refinement of the β-values was performed as an iterative procedure, where the values were updated at each trial/iteration using the leakage volumes obtained by solving the set of steady-state mass balance equations in the model. The optimal value was considered to be the one that corresponded to the leak percentage provided by VAV.

Chapter 8

Results and discussion

8.1 Leakage outflow with new demand patterns

The analysis module in WDNetXL was used to run two different simulations. The demand patterns created by the model developers were used in the first simulation, and the new demand patterns obtained from actual measurements were used in the second. The specific demand and leakage outflow volumes that were returned as a result of the simulations are displayed in Figure 8.1 and Figure 8.2.

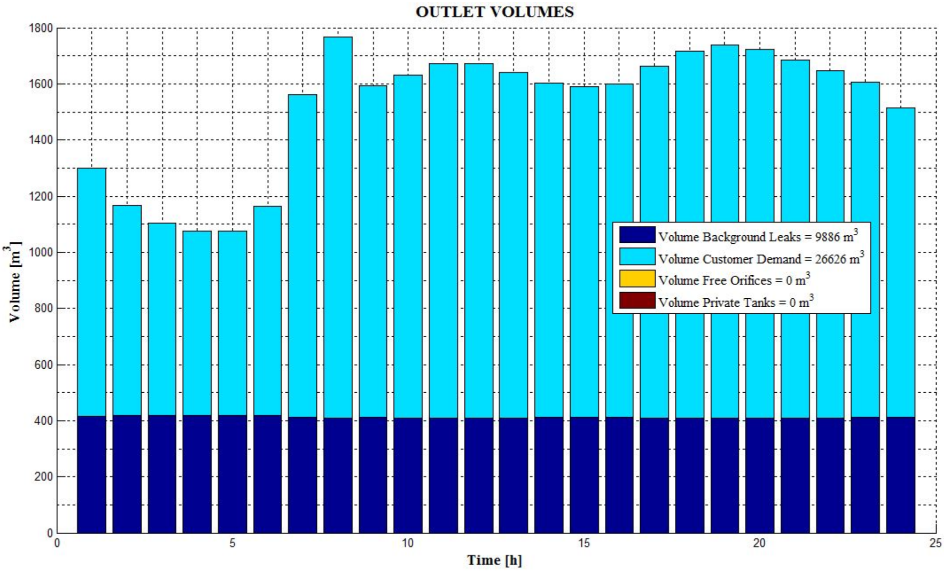


Figure 8.1: Distribution between leakage and demand volume as a result of a simulation with generated demand patterns.

As we can see from the simulation results, the distribution of the total demand

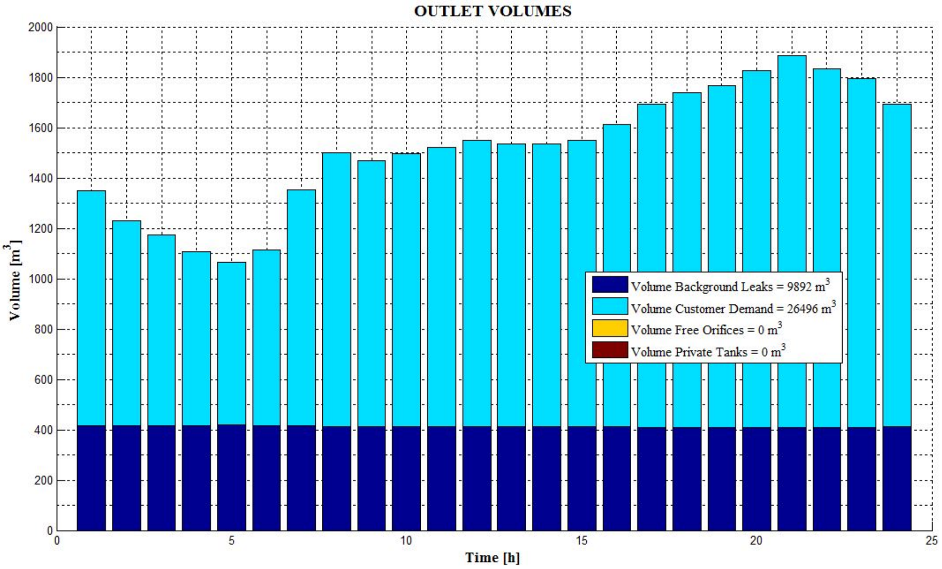


Figure 8.2: Distribution between leakage and demand volume as a result of a simulation with calculated demand patterns from retrieved data.

volume is altered with the new demand patterns. This is expected and logical as the specific volume for a given time step is calculated from the demand factors for the same time step. Therefore, the volume distribution will change together with the demand factors.

The costumer demand decreases from $26626m^3$ to $26496m^3$, and the background leakage volume increases from $9886m^3$ to $9892m^3$. This is equivalent to a leak percentage increase of 0.1087%, which substantially does not have any practical effect.

8.2 Refined β-value from new demand patterns

VAV have worked with estimating leakage levels over a long period of time, and they have had multiple projects on the topic. Although the leak percentage is an estimate at best, it is assumed that the value provided by VAV is accurate in this thesis.

VAV states that the overall leak percentage in the E^3-network is 27.076%. The value increased to 27.185% with the implementation of the new demand patterns. In order to bring the leak percentage down to the original value, the β-value for the network was changed. This can be considered as a small refinement of the model, as the new /*beta*-value will be more accurate. Further description of β can be found in subsection 6.2.6.

The new β-value was found through an iterative process. For each trial/iteration the model ran a simulation, and a new leak percentage was calculated. The β that gave the same leak percentage as VAV provided was considered to be correct. The iterations are shown in Table 8.1.

β-value	$\triangle$	**Leak percentage**
$4.46586e^{-9}$	0.0	27.185
$4.44586e^{-9}$	$-0.02e^{-9}$	27.096
$4.44386e^{-9}$	$-0.022e^{-9}$	27.089
$4.44186e^{-9}$	$-0.024e^{-9}$	27.078
$4.43986e^{-9}$	$-0.026e^{-9}$	27.071
$4.44086e^{-9}$	$-0.025e^{-9}$	27.076

Table 8.1: Iteration process to find new β-value.

The final β value is $4.44086e^{-9}$, which equals a leak percentage of 27.076. The distribution between the demand volume and background leakage with new demand patterns and a new β-value is shown in Figure 8.3.

One of the most interesting results from the model run with new demand patterns and a refined β-value was that the overall demand and leakage volume almost did not change at all. This was not expected, given the fact that the original model was based on several assumptions. The reason why this happens might be:

- The system is oversized. This means that the change in demand patterns will only have a small effect on the pressure regime in the system and therefore also on the overall leak percentage.
- The pressure regime in the system is highly dependent on water pumps and PCVs because of the topography. This means that they will compensate the pressure proportionally with the changes in demand. The changes in demand will therefore have a small effect on the pressure and on the overall leak percentage.
- The pressure conditions in the network are not properly simulated in the model due to several uncertainties (see section 8.3).
- The assumptions made in the model development may be very good. The information that was provided by VAV had a high degree of deficiency, and several assumptions had to be made by the model developers at IDEA-RT. The

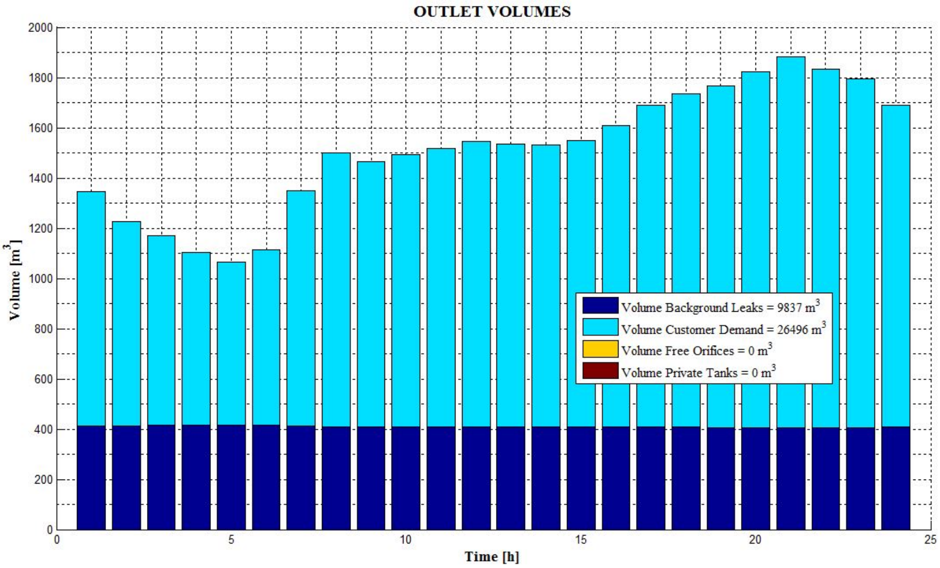


Figure 8.3: Distribution between leakage and demand volume as a result of a simulation with calculated demand patterns from retrieved data and a refined β-value.

fact that the results obtained from using actual retrieved data does not differ all too much from the original model may indicate that the assumptions are valid and able to represent the actual system.

8.3 Uncertainties

8.3.1 Uncertainties in the logged data

No measurement is ever exact. The accuracy and precision of a measurement is always limited by the refinement of the equipment that is performing the measurements. There are a couple of uncertainties in the data logged in the historian database that are important to be aware of, especially if the data is to be used for further analysis, e.g. in a hydraulic model.

Uneven data storage

As previously stated in chapter 4, it is important to note that logged data is not typically stored at even intervals. "Bad" loggings can occur quite often. By retrieving data at other intervals than the ones logged by the measuring meter/sensor, the values will be automatically averaged and/or interpolated to create results based on a the given user specified, evenly distributed, time interval. This can produce results that do not actually represent the reality. Figure 8.4 shows an example of a logged data sample with uneven storage in the historian.

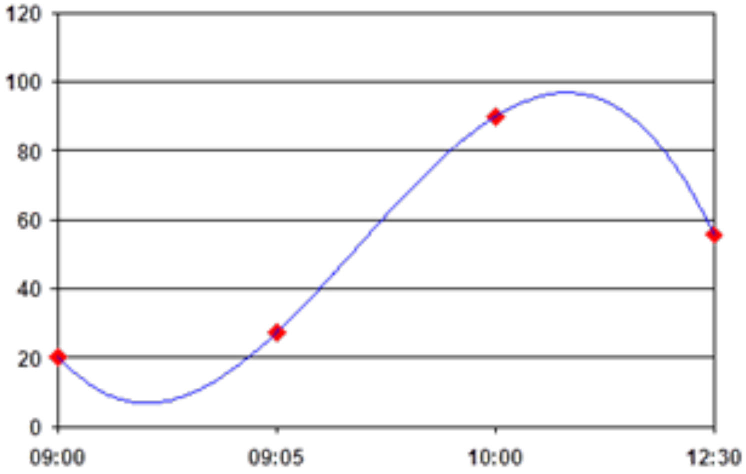


Figure 8.4: Example of uneven storage of logged data. The red dots represents logged data, and the blue trend line is a third degree polynom calculated by polynomial interpolation (edited from (Friedenthal, 2007)).

The trend line in Figure 8.4 is an interpolated line. This is an example where a line has been interpolated between raw samples and returned as a continuous graph. The maxima in this graph occurs just after 10:00. It is important to note that this value is not logged, it is calculated. This means that it may not be an actual maxima, and therefore it can produce wrong results if it where to be used for further analysis, e.g. in a hydraulic model.

Comparing measurements

The sensors in the network are not synchronized, which means that each sensor do not measure flow and/or pressure at the same time step. One meter may have a measurement every minute, and another every 40th second. This means that data from two different measuring points are not necessarily directly comparable. The data needs to be broken down to an equal time resolution for the comparison to be valid. This is important in e.g. mass balance calculations between measuring points in the same DMA.

Direct calculation and information loss

Figure 8.5 displays a graph created from data that was retrieved from MK104 at three different user specified, evenly distributed, intervals (1hr, 30-min, and 15-min). The data was automatically averaged and interpolated in the retrieval process, and the result is a continuous graph. As we can see from the graph, more information is lost in the process when the resolution of the retrieved data is lower. More "bad" loggings occur over an hour than over 30-min, and the system will interpret the "bad" loggings as zero. This explains why the highs and lows are less apparent for the hourly intervals than for the other two. However, it is very important to note that a “bad” value is not the same as 0. There is a flow and a pressure occurring, but it is not logged and stored in the historian as a value. The graph in Figure 8.5 is therefore only a simplification, at best, of the real world process.

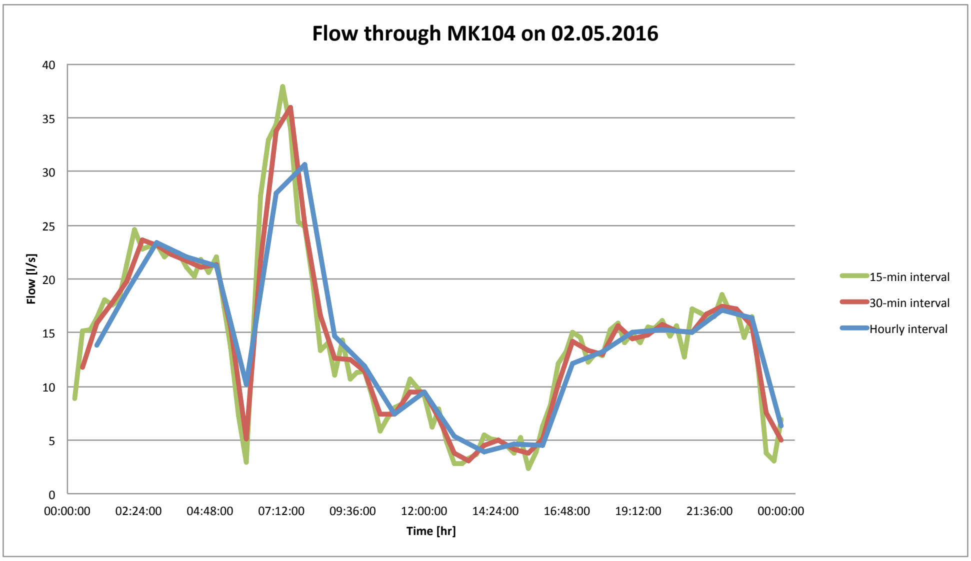


Figure 8.5: Logged data sampled at different intervals (1hr, 30-min, 15-min). The values are automatically averaged and interpolated in the retrieval process. The graph shows that maximum and minimum values are not displayed correctly with lower resolution samples (Oslo Water and Sewerage Works (VAV), 2016).

Faulty measurements by meter/sensor

The meters and sensors within the system are not always installed and maintained by people who have knowledge about their specific use. Therefore, the equipment may be subject to faulty instalment. There are reports stating issues with measuring equipment, e.g. the set points of meters and sensors, where the measurements have had an error up to fifty percent (Oslo Water and Sewerage Works (VAV), 2016). This is not a problem in the daily use of the system at VAV, as the measurements mainly is used for monitoring purposes. Abnormalities would still be detectable, as long as the equipment has a constant error. However, erroneous measurements will produce wrong results if they were to be used for further analysis, e.g. in a hydraulic model.

8.3.2 Uncertainties in the calculations

Several calculations have been made in order to create new demand patterns. An effort has been made to minimize the uncertainty of these calculations. However, there are some that are hard to avoid. The main uncertainties that should be noted are listed below:

- As previously stated, some information get lost every time an average is used. The discrete time series created from the calculated means are considered to be representative in this thesis. However, it is important to note that these series are not the same as the actual measurements.
- The significance level for the ANOVA test was set to $\alpha = 0.05$, which means that there is a 5% chance that the null hypothesis is rejected when it is actually true.
- Propagation of error will occur as there are uncertainties related to every measurement that the calculations are based on, due to limited instrument precision.

8.3.3 Uncertainties in the model

There are some assumptions in the model which can be regarded as uncertainties. All assumptions are listed in the restricted report "Hydraulic model of E3network water distribution network in WDNetXL" written by the IDEA-RT team. The ones worth noting are listed below.

Pumps and pressure reduction valves

All information about the pumps in the network are withdrawn from the EPANET*.inp file provided by VAV. The network has 16 pumps divided into 5 pumping stations. There are only 5 pumps that are classified as open, which are located in three different pumping stations. Closed pumping stations have no effects on the hydraulic behaviour of the rest of the network.

Even though 11 pumps are marked as closed in the EPANET file does not mean that this is actually true. Working with iFix and the ArcMap database revealed that the pumping stations are in operation and that the operation of the pumps within each station is dependent on the pressure conditions in the network. Also, the pumps are operated in turn to even out the wear of the pumps. Pumping curves provided by VAV are limited, e.g. one pumping station only has a curve for one pump even though it consists of 3 pumps.

This fact may have a significant effect on the modeling of the network, since the pressure regime in the system is highly dependent on water pumps and PCVs because of the topography.

The same goes for the pressure reduction valves (PRVs) in the system. 17 of the 44 PRVs are marked as closed. The model developers have no other option than assuming that this is true, but it may not actually be the case.

However, it is important to note that the modeling results are valid based on the data supplied by VAV.

Demand patterns

The number of demand patterns have been decreased from 34 to 13 since many of the patterns does not correspond to specific nodes. This simplification may be valid, but it poses an uncertainty nonetheless.

Background leakages

The leakages reported in the EPANET model are assumed to represent background leakages lumped at network nodes. No information about major leaks was reported by VAV.

The α value is assumed to be the same for the whole network, given the uncertainties surrounding the information provided about the network. The β value is assumed to be 0 for short pipes (length less than 2m) and a unique β is applied to pipes with ending nodes belonging to the same group of leakage nodal demands. There are 10 different groups, and the β chosen to represent the whole system is the average of these. This means that β has a constant value for the entire system. The assumption of a constant value throughout the network may hold for α, but β will most likely vary within a wider range of variability. The reason is that β exponentially increases at a rate whose coefficient is dependent on the pressure regime in the system. β also depend on pipe conditions, and for this reason, its more accurate to divide the pipes into groups that have the same characteristics and apply a unique β-value to each group.

Chapter 9

Concluding remarks

9.1 Conclusion

The specific tasks of the thesis includes:

1. Build competence on the use of the hydraulic model WDNetXL in use at VAV.

   I have used WDNetXL to perform several simulations. Also, I have modified the model by changing the demand factors and the β-value. The process is described in chapter 7, and the results are presented in chapter 8.

2. Get an overview of the operational conditions for the selected pilot in Oslo and describe them as basis for the following work.

   I have gained in-depth knowledge about the operational conditions in Oslo through iFix and the ArcMap database, and through the process of retrieving data from the data historian. However, almost nothing has been described in the thesis due to security issues.

3. Get an overview of the SCADA system in use at VAV.

   An overview of the SCADA system has been provided by the ICT department at VAV. Also, in-depth information about SCADA systems in general has been acquired through literature. The principles of online modeling and SCADA systems are described in chapter 3, and the system in use at VAV is described in chapter 4.

4. Define the data and format needed in the E^3-network model.

   This had to be done in order to retrieve the right information from the data historian, and to be able to create new demand patterns. All work related to the E^3-network model is described in chapter 4 and chapter 7.

5. Retrieve data in the right format from the historian database.

A great effort was made to retrieve good quality data from the data historian. Useful insights about the process has been provided in chapter 4.

6. Exemplify how the model can be refined with the use of actual data.

   An example of how the data can be used to refine the model has been provided in chapter 7 and chapter 8. It is important to note that the data can be used in a far more sophisticated way than the one applied in this thesis. This, however, requires the use of other modules in the WDNetXL platform, e.g. the management module.

There are three main contributions to the E^3 project from this thesis:

1. An analysis of the specifications of a specific SCADA system in order to retrieve consistent data in the right format. The data is formatted for calibration of hydraulic models.

   Data has been retrieved from the data historian. However, a method for retrieving consistently good quality data has not been provided. "Bad" loggings remains a problem, one that should be adressed if VAV wants to take use of RRTC in the future.

2. A relatively simple method for retrieving data from the central SCADA database (historian) is presented, along with comprehensive theory regarding the data quality. An example of how the data can be formatted and used in WDNetXL is also included.

   The thesis provides useful insights on how data can be retrieved, formatted, and used in WDNetXL.

3. Real-world data is retrieved to help refine the first iteration of the model. The calibration will make the model more representative, and make the simulations more accurate.

   The model has not been calibrated although real-world data has been retrieved. The model has been refined, but there is still a lot of work that has to be made in order for the model to take full use of the retrieved data, and also to ensure the quality of the data used. It is important to note, however, that IDEA-RT have considered the information provided by VAV as reliable and certain. This was done because VAV claims that the EPANET*.inp file is calibrated.

9.2 Limitations

The retrieved data was not exploited to its full potential in this thesis. Originally, both the pressure and the flow measurements were to be used to create new demand patterns. There are two reasons for why this was not done: The first is that the management module of WDNetXL would be needed in order to take full use of the data. The second is that it was hard to find good quality data sets for both pressure and flow at the same sample period, and not least very time consuming. Therefore, a simplification was made were the flow data was manipulated mathematically to create new patterns. Both the flow and pressure data should be exploited to refine the model further in the future.

Also, the data could be used to calculate MNF for the different DMAs in the network, in order to calculate a better estimate of the leakage level for each DMA and for the entire network. Flow patterns from a specific period in one year could for instance be compared to the flow patterns for the same period the year before, to see if there are any abnormalities. An example of this is shown in Figure 9.1. As we can see, there is a small difference in the MNF in the two graphs, which may indicate a leakage in the DMA.

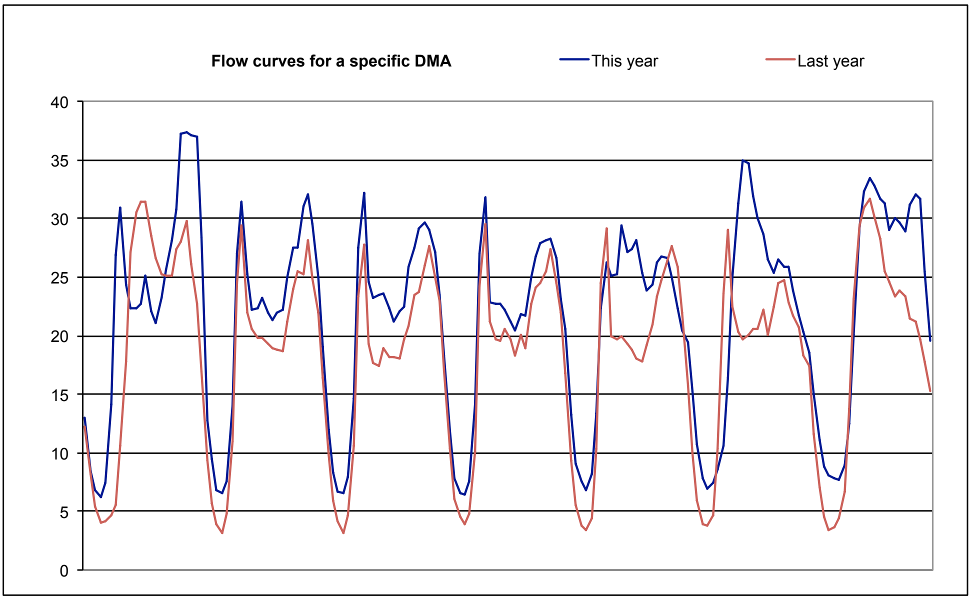


Figure 9.1: Flow pattern from a specific period in one year is compared to the same period in the year before.

9.3 Summary

The water distribution system conveys water from the WTP to the user. A significant amount of the water is lost in this transit. IWSA claims that the amount is typically

20-30% of the total water production depending on the overall state of the distribution system (Hunaidi et al., 2000). There is a great variation of the pipe material and the quality of construction of trenches for pipelines. Therefore, some distribution systems may lose as much as 50%. IWSA made a survey, which stated that the major cause of unaccounted for water loss is leakage. VAV wants to investigate options to optimize the efficiency of water used, and of the water demand strategies, to increase the reliability of the service provided. The motivation for this is that future projections for water demand in Oslo resulting from population growth are considered unacceptable. One of the approaches to the combined problem of increasing water demand and rehabilitation of the network is to improve the water demand management.

E^3WDM is a SINTEF project which goal is to promote new thinking and smart innovations in the water service. The ultimate goal of the project includes the use of ICT solutions to adapt and upgrade existing water infrastructure of Oslo to support a more efficient, effective and economic water demand management in the growing city. This thesis contributes to the work of work package 2 (WP2) in the project, which focuses on the E^3 pilot network.

The thesis has focused on analysing the specifications of a SCADA system to be able to retrieve consistent data, in the right format, in order to calibrate a HNSM. Among the main results from the thesis is the establishment of a link between a centralized SCADA database and a HNSM. Useful insights in data extraction has been provided together with an example of how the data can be used in model refinement. A pilot system of the water supply in Oslo, called the E^3-network, have been used as an example.

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