B-WaterSmart

NTNU
Norwegian University of Science and Technology

Training Event LL Bodø/ Norway

Topic: Water distribution system modelling, optimization, and leak detection

As Part of our B-Watersmart (https://b-watersmart.eu/) training events we invite the Norwegian Partners as well as other interested Norwegian municipalities, utilities, consultants, researchers, and students to an online event with multiple presentations.

The event will take place on the 10th of February. Please subscribe using the following link before the 7th of February: https://form.jotform.com/230243281165347

Program:

09:00-09:10:	***Short Introduction of the project***
09:10-09:40:	Presentation Karel van Laarhoven (KWR): ***Optimization for water distribution systems***
09:40-09:50	Questions
09:50-10:00	Presentation Prasanna Mohan Doss (NTNU): ***Variable Autoencoders for Leak detection***
10:00-10:05	Questions
10:05-10:15	Presentation Erik Nordahl (Multiconsult/NTNU): ***Dual model for leak localization***
10:15-10:20	Questions
10:20-10:30	Presentation Bulat Kerimov (NTNU): ***Graph Neural Networks for Water distribution system modelling***
10:30-10:35	Questions
10:35-10:45	Presentation Shamsuddin Daulat (NTNU): ***Evaluating the generalizability and transferability of water distribution deterioration models***
10:45-10:50:	Questions
10:50-11:00:	***Discussion***

B-WaterSmart

Accelerating Water Smartness in Coastal Europe and beyond

Horizon 2020 project
Call: H2020-SC5-2018-2019-2020
Greening the economy in line with the Sustainable Development Goals (SDGs)

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Faculty of Engineering

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b-watersmart.eu

B-WaterSmart accelerates the transformation to water-smart economies and societies in coastal Europe and beyond

The project is:

- Grounded on **6 coastal European cities and regions** as 6 interconnected **Living Labs (LLs)**
- Supported by Communities of Practice (**CoPs**) and **a European Innovation Alliance** (INALL)
- Promoted by the Aqua Research Collaboration **ARC –** A Network of European Water Research Institutes

arc

B-WaterSmart

B-WaterSmart project partners

IWW Zentrum Wasser
adelphi
adene Agência para a Energia
Águas do Tejo Atlântico Grupo Águas de Portugal
AA
Aquafin
baseform
bodø kommune
CETAQUA Water Technology Centre
De Watergroep
depuracque servizi srl
dmk Group
Engineering
Technology for Water EnviroChemie
ETRA Futuro sostenibile
eurecat Centre Tecnològic de Catalunya
HT Engineering Hydrotech Advanced Water Technologies
i-Sense Group
ICS Instituto de Ciências Sociais, Universidade de Lisboa
Krüger Kaldnes
KWR
LNEC Laboratório Nacional de Engenharia Civil
Lisboa Câmara Municipal
Lisboa Capital Verde Europeia
Mechelen
nordkontakt
NTNU Norwegian University of Science and Technology
OOWV
Proefstation voor de Groenteteelt
SINTEF
TECHNI
Turbulent
UNED
Veritas
vito
Water Europe Technology & Innovation

B-WaterSmart LIVING LABS

1 Alicante

Challenges
Water scarcity, limitations to water reuse due to high salinity/nitrates, limitations to water reuse due to low acceptance.

Innovation & Demonstration
Improve water-smartness in the municipality of Alicante by incrementing water reuse and boosting circular economy opportunities.

2 Bodø

Challenges
Growing resident population and economy, increased pollution, untapped efficiency potential.

Innovation & Demonstration
Zero emission urban development, improved management of the wastewater stream, improved air quality.

3 East Frisia

Challenges
Increasing water demand in supply area by growing sectors (households, industry, agriculture), limited groundwater resources, locally untapped water reuse potential.

Innovation & Demonstration
Increasing the carrying capacity of water supply: Identification of alternative resources, intelligent protection strategies for groundwater bodies and improved treatment of process water for reuse in milk production.

4 Flanders

Challenges
High drinking water demand due to dense population, high water demand for agriculture, groundwater overexploitation, water quality deterioration, water scarcity due to droughts, climate change and urbanisation.

Innovation & Demonstration
Development of regional concept for improving and monitoring water-smartness and a more robust water system, with a focus on safe water reuse.

5 Lisbon

Challenges
Growing population and economy depend on distant freshwater resources with increasing climate challenges (e.g. droughts and floods). This demand must be balanced with the need to increase urban green areas to ensure the quality of life of citizens and the sustainability of urban life.

Innovation & Demonstration
Development of tools & processes to facilitate safe water reuse, improvment of water-energy-phosphorous efficiency in municipal non-potable water uses, improvement of households and buildings' climate readiness regarding water and energy with an assessment/certification tool developed locally but with an ambition for national/European adoption.

6 Venice

Challenges
Need for reuse and recovery schemes for wastewater & sludge, limitations to reuse and recovery due to low acceptance, water scarcity, untapped efficiency potential (water and resources valorisation).

Innovation & Demonstration
Enable and complete the water reuse (industrial, agricultural and urban) goal of a regional/national plan for lagoon protection, apply nutrient recovery technologies to waste water treatment plants (WWTPs) and develop shared evaluation model-tools for the sustainability of WWTP effluents and sludge valorisation.

B-WaterSmart LIVING LABS

2 Bodø

Challenges

Growing resident population and economy, increased pollution, untapped efficiency potential.

Innovation & Demonstration

Zero emission urban development, improved management of the wastewater stream, improved air quality.

1 Alicante

Challenges

Water scarcity, limit reuse due to high sa limitations to water acceptance.

Innovation & Demon

Improve water-sma municipality of Alica ting water reuse an economy opportunit

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Challenges

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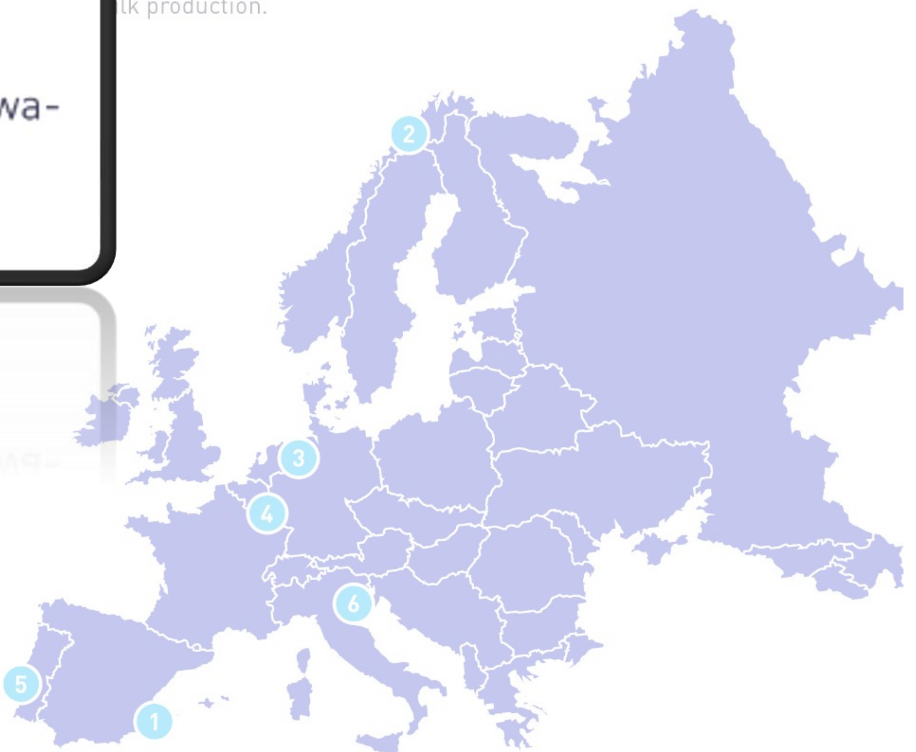
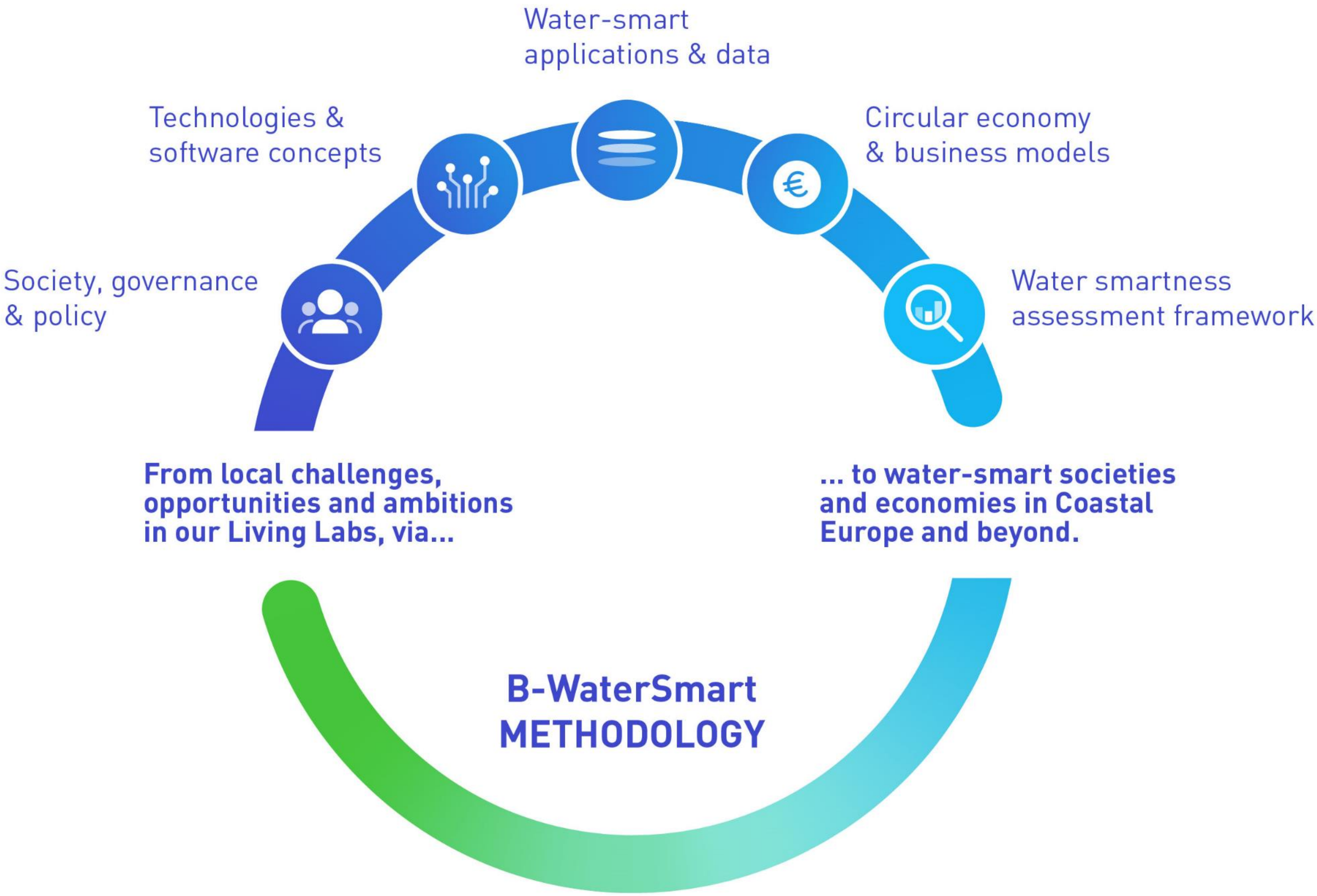
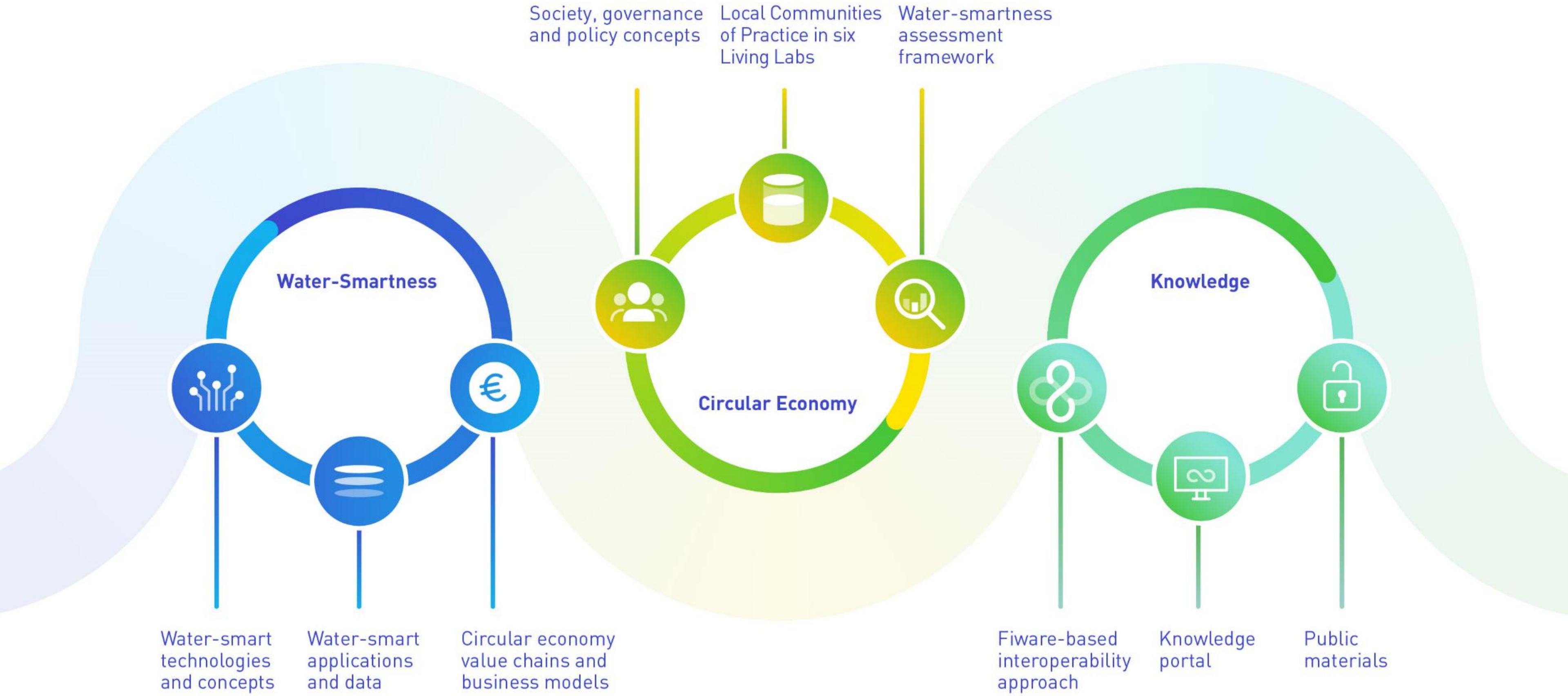



Water-smart applications & data
Technologies & software concepts
Circular economy & business models
Society, governance & policy
Water smartness assessment framework
From local challenges, opportunities and ambitions in our Living Labs, via...
... to water-smart societies and economies in Coastal Europe and beyond.
B-WaterSmart METHODOLOGY

B-WaterSmart MAIN RESULTS



Research goals in B-Watersmart for Living Lab Bodø

Concepts for water-smartness & their technological indicators

- Leakage detection and localization in Water Distribution Networks (WDNs)
- Infiltration in Wastewater Collection System
- Smarter stormwater management
- Potential for biogass production from small decentralized wastewater treatment plants

Partners:

Living Lab: Bodø Kommune

Industry Partners:

1. Nordkontakt – Data collection and Analysis (IT & Communication)
2. TECHNI – Leakage & infiltration detection sensors (IIoT – LPWAN / nb-IoT)

Research Partner: NTNU and SINTEF

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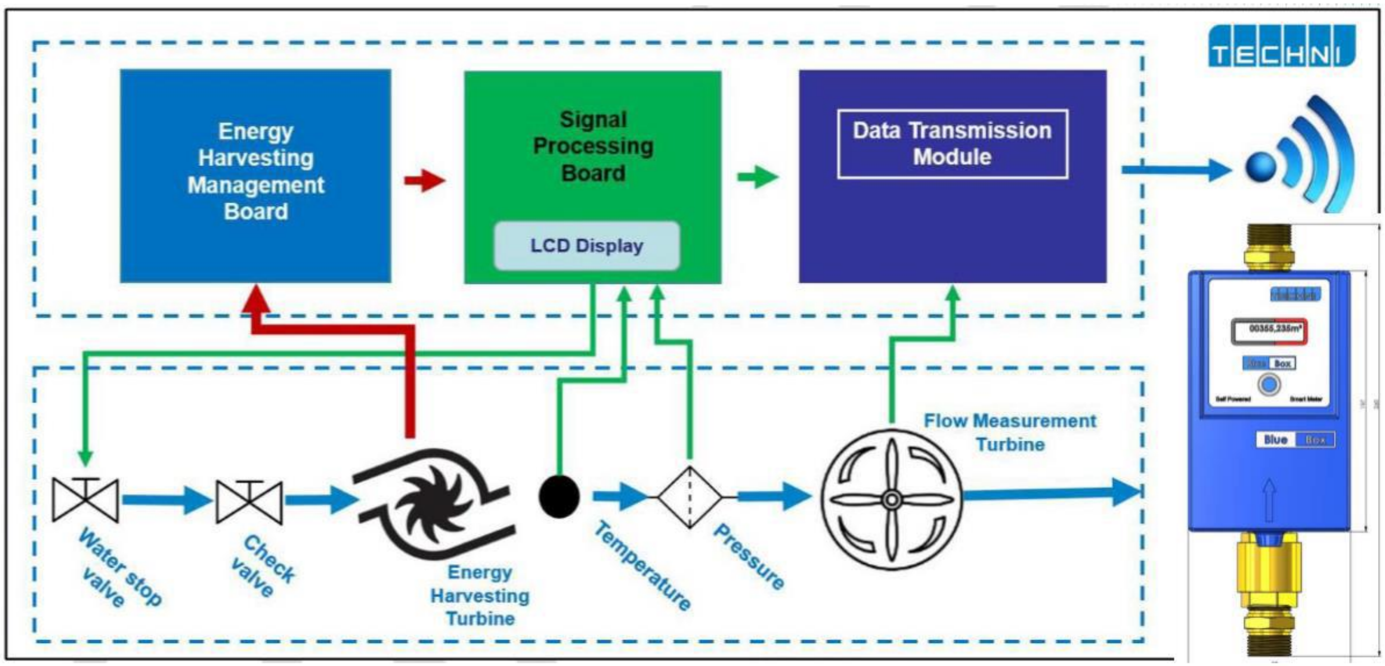
Technologies

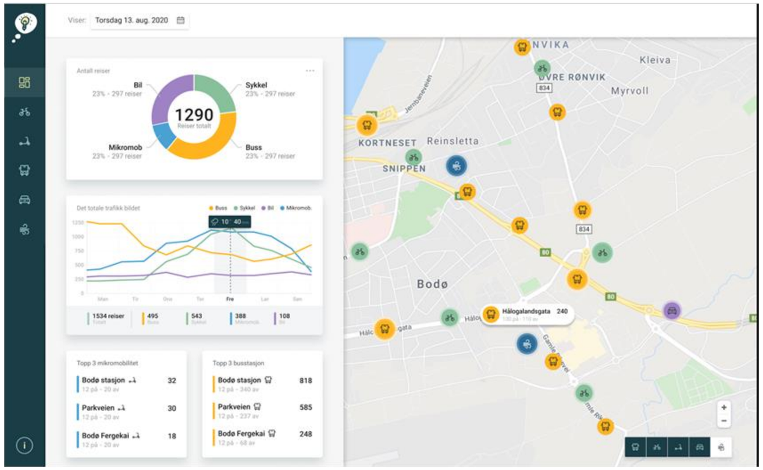


Technologies

Dashboard for Bodø Living Lab in B-WaterSmart

1. Design a framework for visualizing different themes.(dashboard/GUI)
2. Develop the framework.
   - *The design work with principles has now been completed, and a solution has been established.*
   - *Compile available measurement data from online sources. (obtain data from current operational monitoring systems, open data, etc.)*

Tools



Test our plattform at:

https://www.miljodashboard.no/

nord|kontakt

Technologies

Tools

Algorithms

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Questions

B-WaterSmart

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 869171. The publication reflects only the authors' views and the European Union is not liable for any use that may be made of the information contained therein.

NTNU - February 10th 2023

Optimization for drinking water networks

Karel van Laarhoven, KWR

KWR

Bridging Science to Practice

KWR Water Research Institute

applied water research

The Water Infrastructure Team


Mirjam Blokker


Bram Hillebrand


Karel van Laarhoven

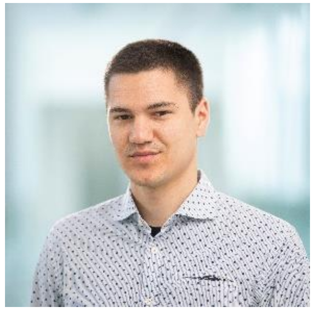

Jan Vreeburg


Ralph Beuken


Joost van Summeren


Amitosh Dash


Quan Pan


Djorde Mitrovic


Aulia Galama

Mohamad Zeidan

KWR

- Water Quality
  - chemical
  - microbiological
  - sediment
- Future-proof Network Design
  - water demand
  - smart networks
  - design philosophy
- Asset Management
  - network condition
  - operation and maintanance
  - multi-utility

The Water Infrastructure Team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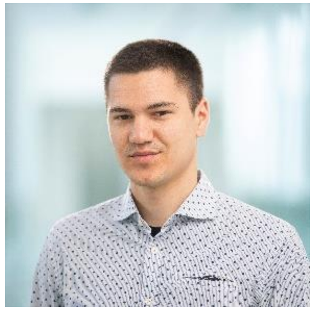
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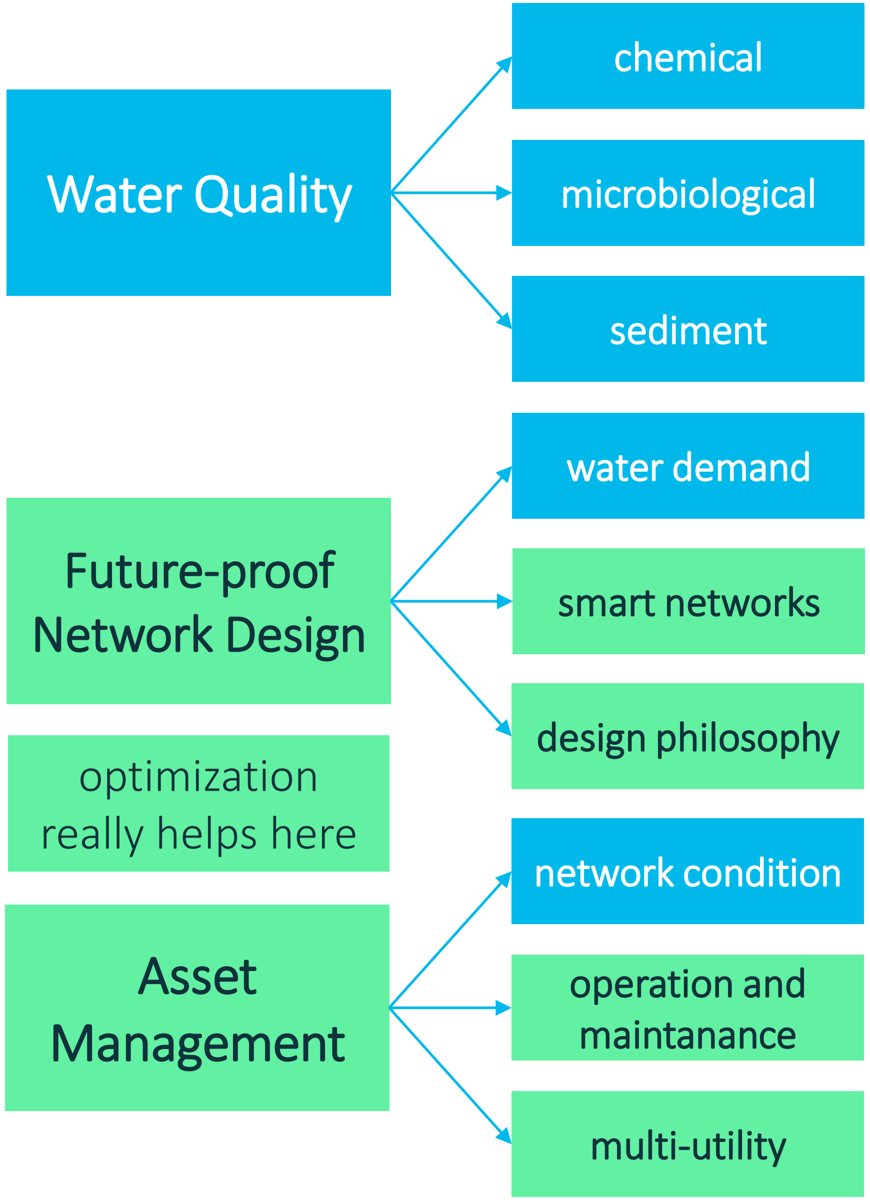


Network Optimization

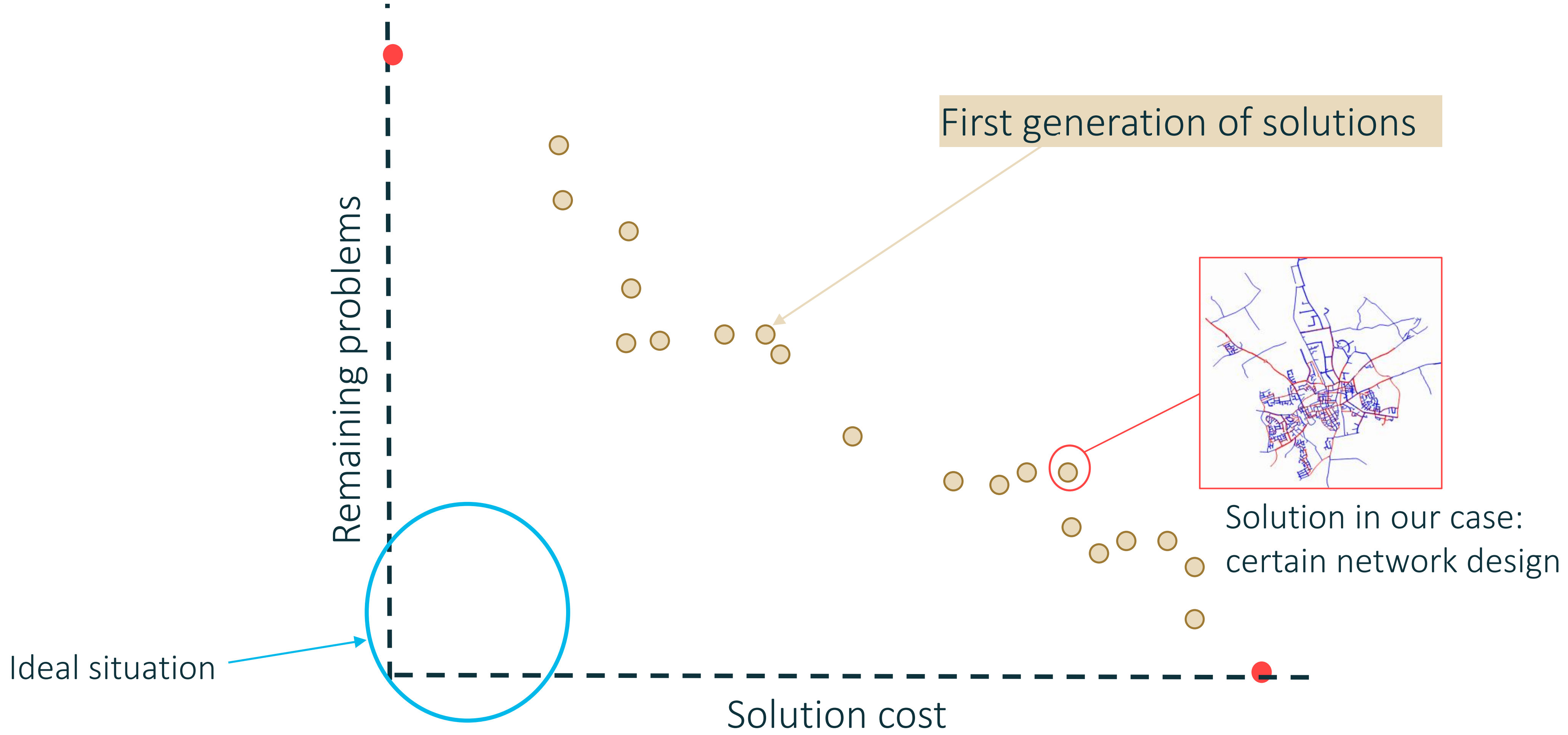
Numerical optimization

Family of mathematical tricks to efficiently explore and compare a multitude of possible solutions

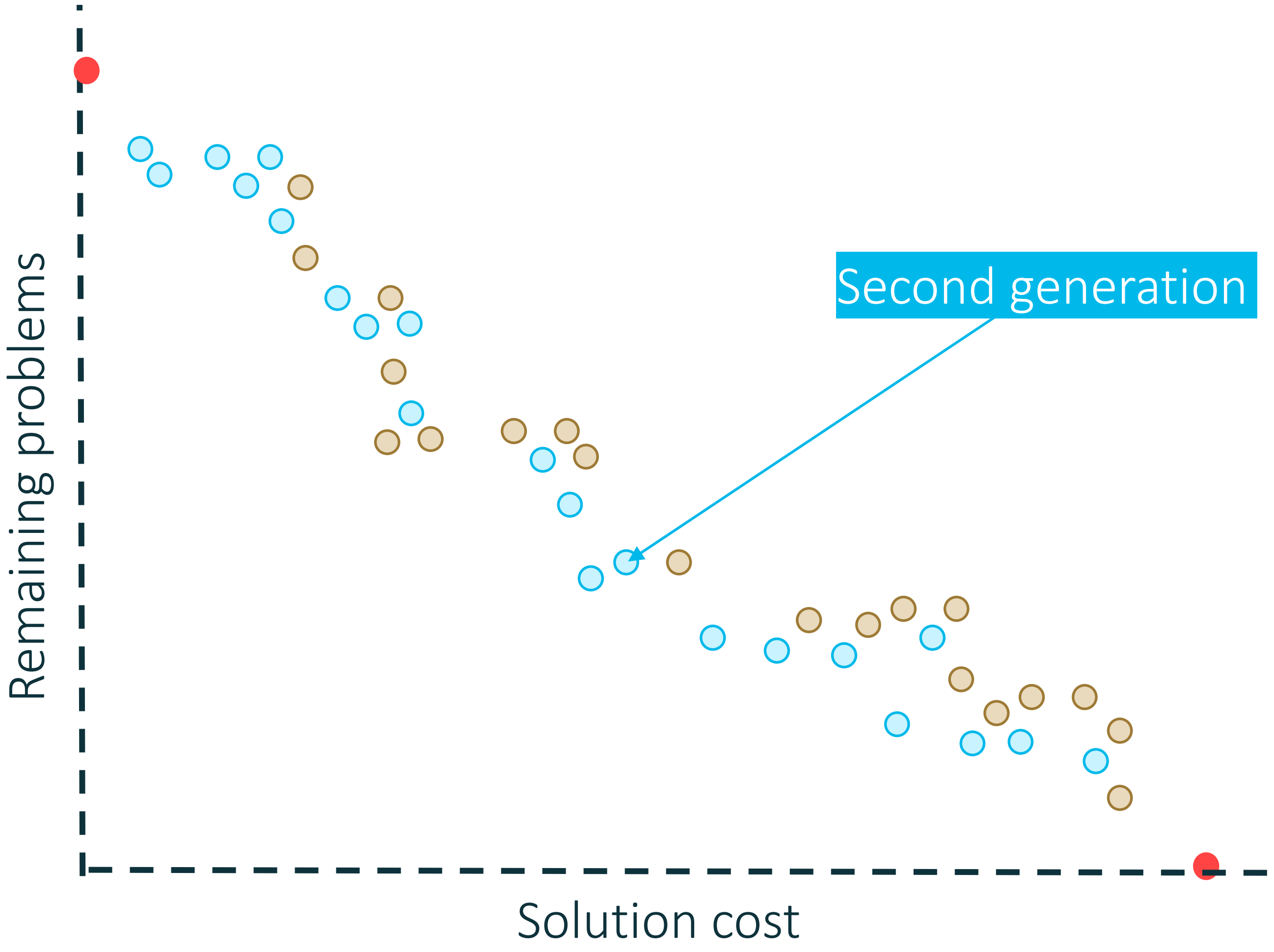
Key mathematical ingredients:

• description of solutions	(design variables)
• judging of solution quality	(objectives & constraints)
• proposal of (new) solutions	(variator)

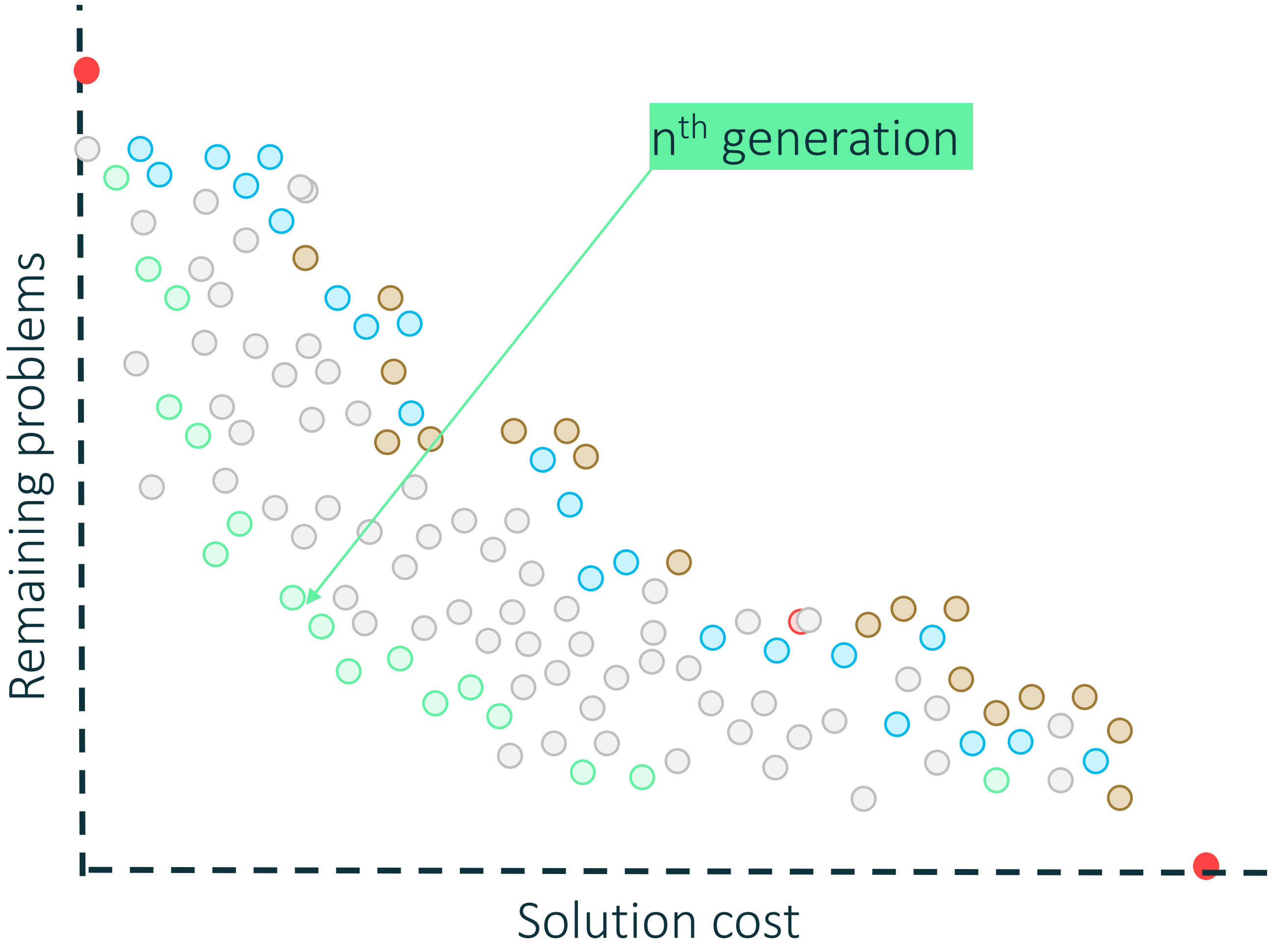
Numerical optimization



Numerical optimization



Numerical optimization



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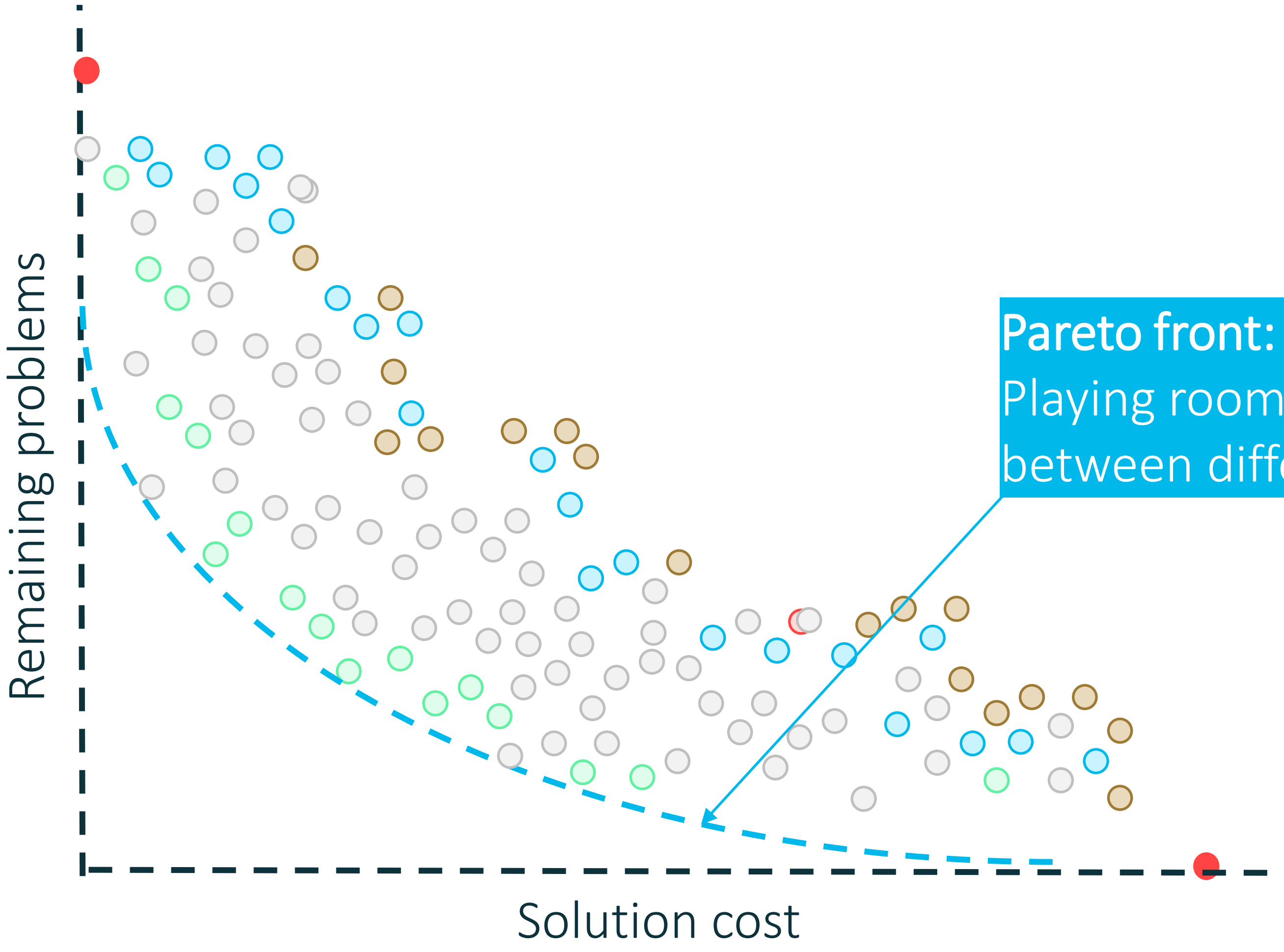


Optimization at drinking water utilities – Why?

(given that we have been tackling any number of complex design question by hand just fine, so far)

Forced to approach the goal mathematically

- Enhances insight in questions/goals
- Makes choices more objective
- Makes intuition more reproducable/transparant

Hopefully capture some knowledge of the older generation

Optimization = robust automation

- Room to explore and adjust 'with a push of the button'
- This supports ideation and re-evaluating rules of thumb
- Once develloped, the approach is extremely re-usable

Hopefully supports the soon to be overloaded younger generation

(Optimization = 'optimal')

Optimization at drinking water utilities – approach

Gondwana

Swiss army knife software tool to help with:

- formulating,
- analysing,
- solving

a multitude of different, complex network design questions.

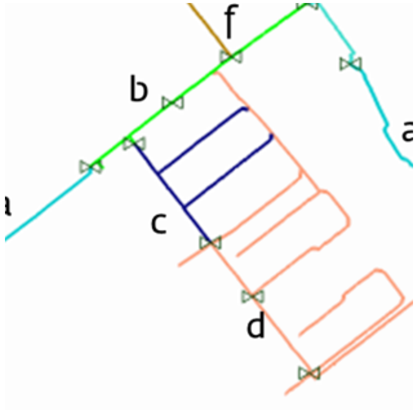
Main strength: a design focussed on maximum flexibility in problem formulation

Inside: Epanet, hybrid evolutionairy algorithms and accumulating research scripts.

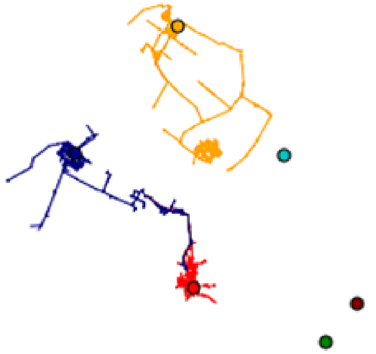
Gondwana®

MASTER PLANS

PRIORITIZATION



SENSOR PLACEMENT



VALVE SECTION DESIGN

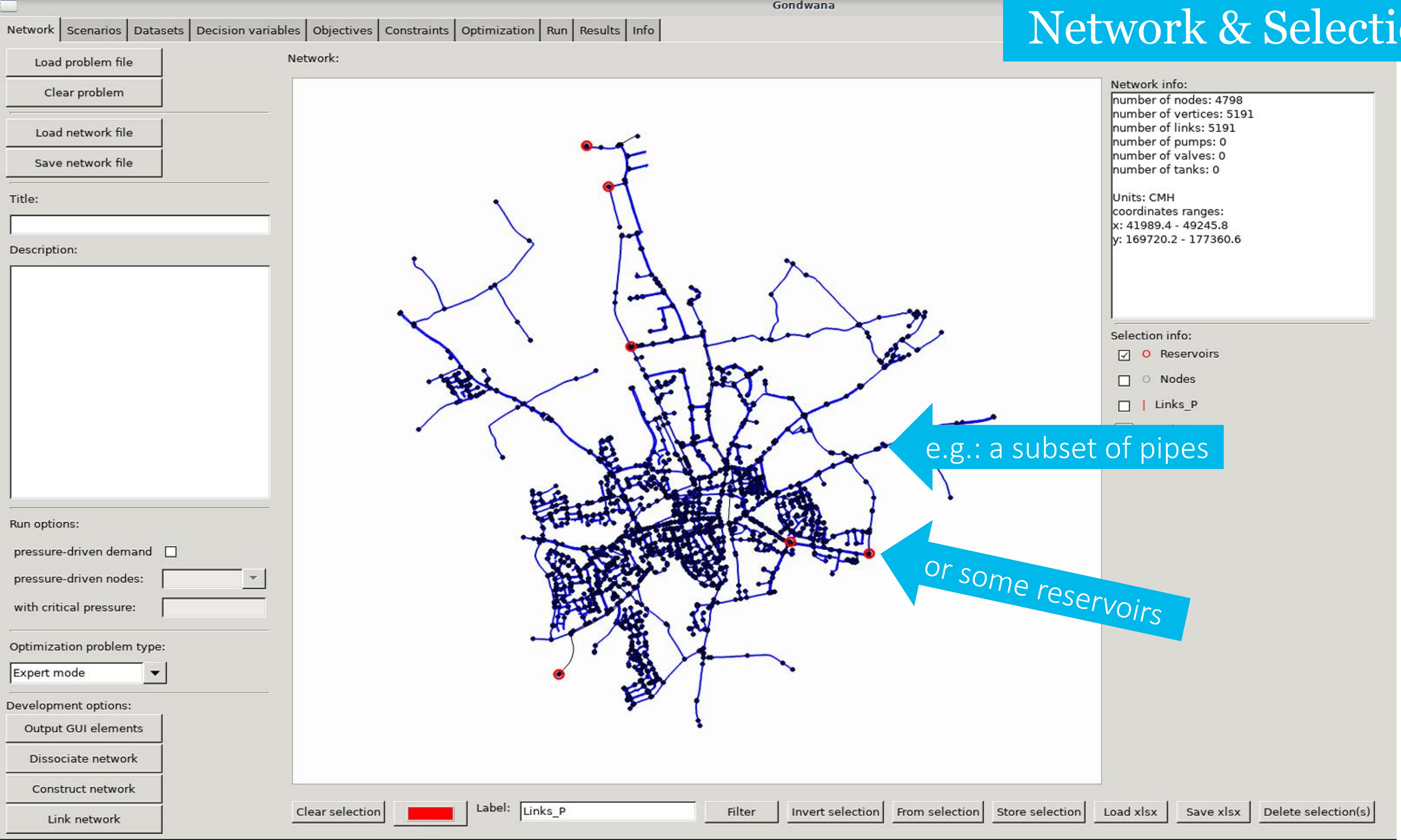
CALIBRATION

FLUSHING PLANS

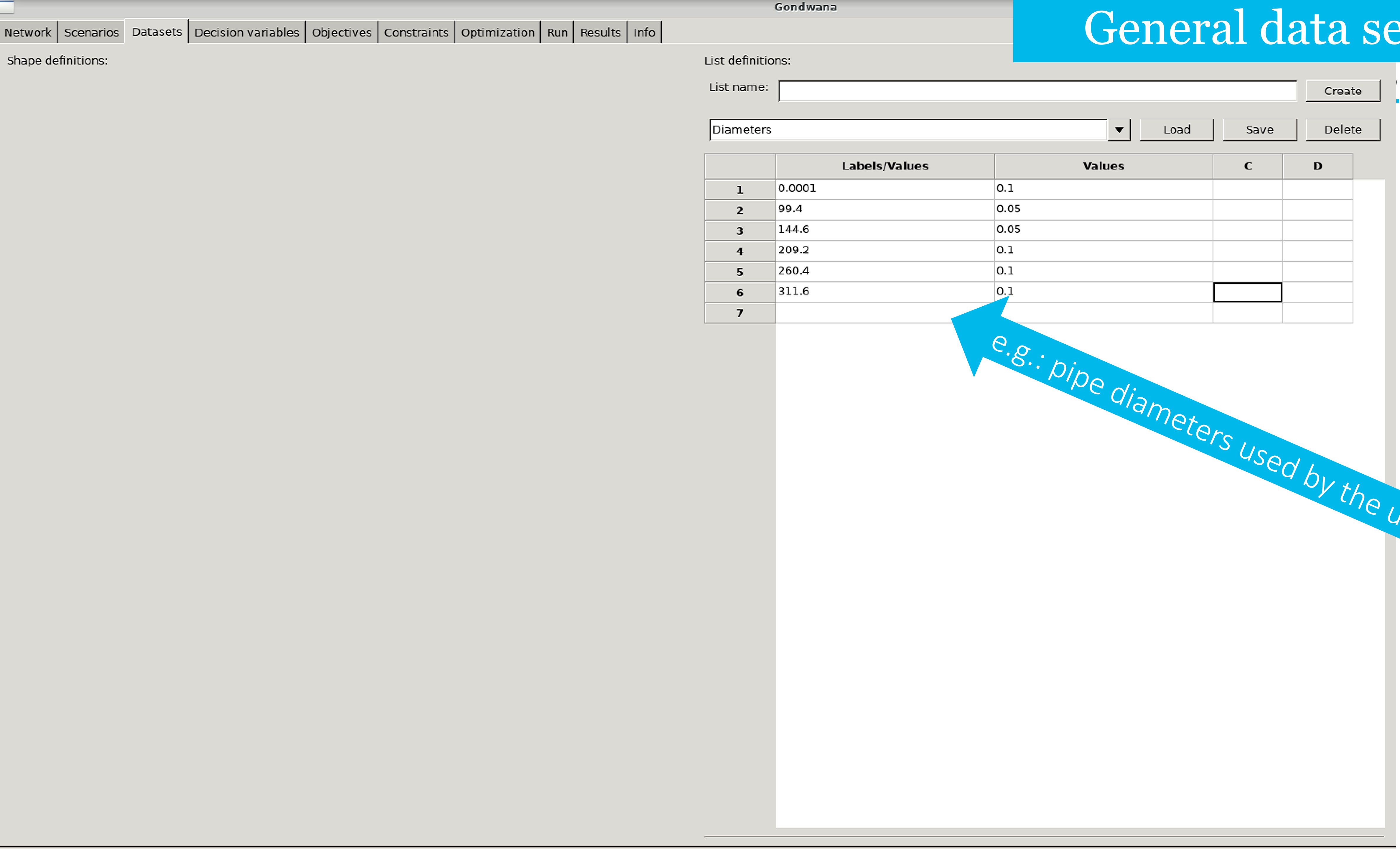
CALAMITY RESPONSE

…

Network & Selections



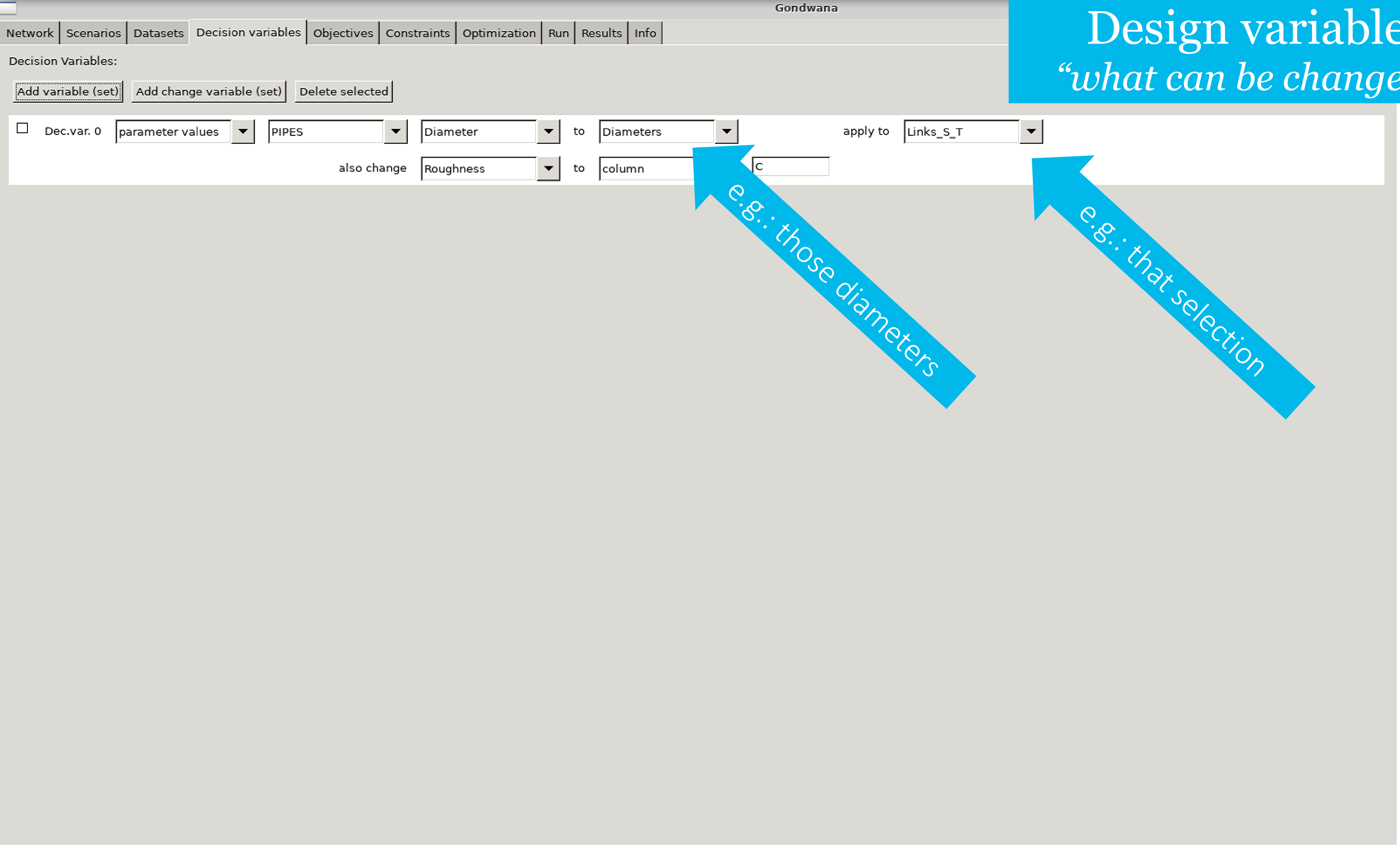
General data sets



e.g.: pipe diameters used by the utility

Design variables

“what can be changed?”



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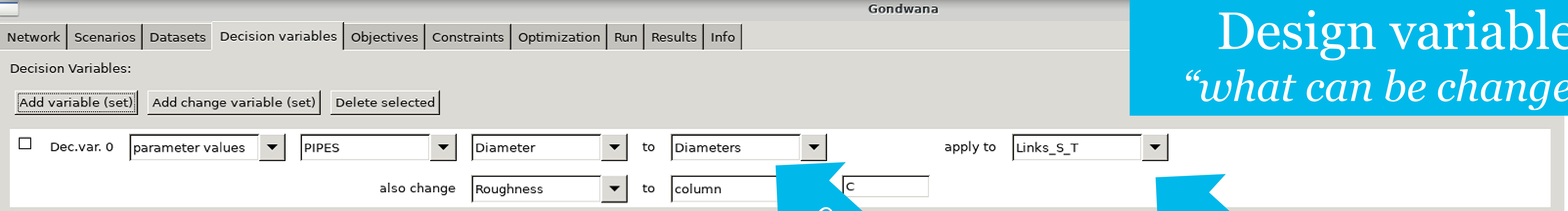


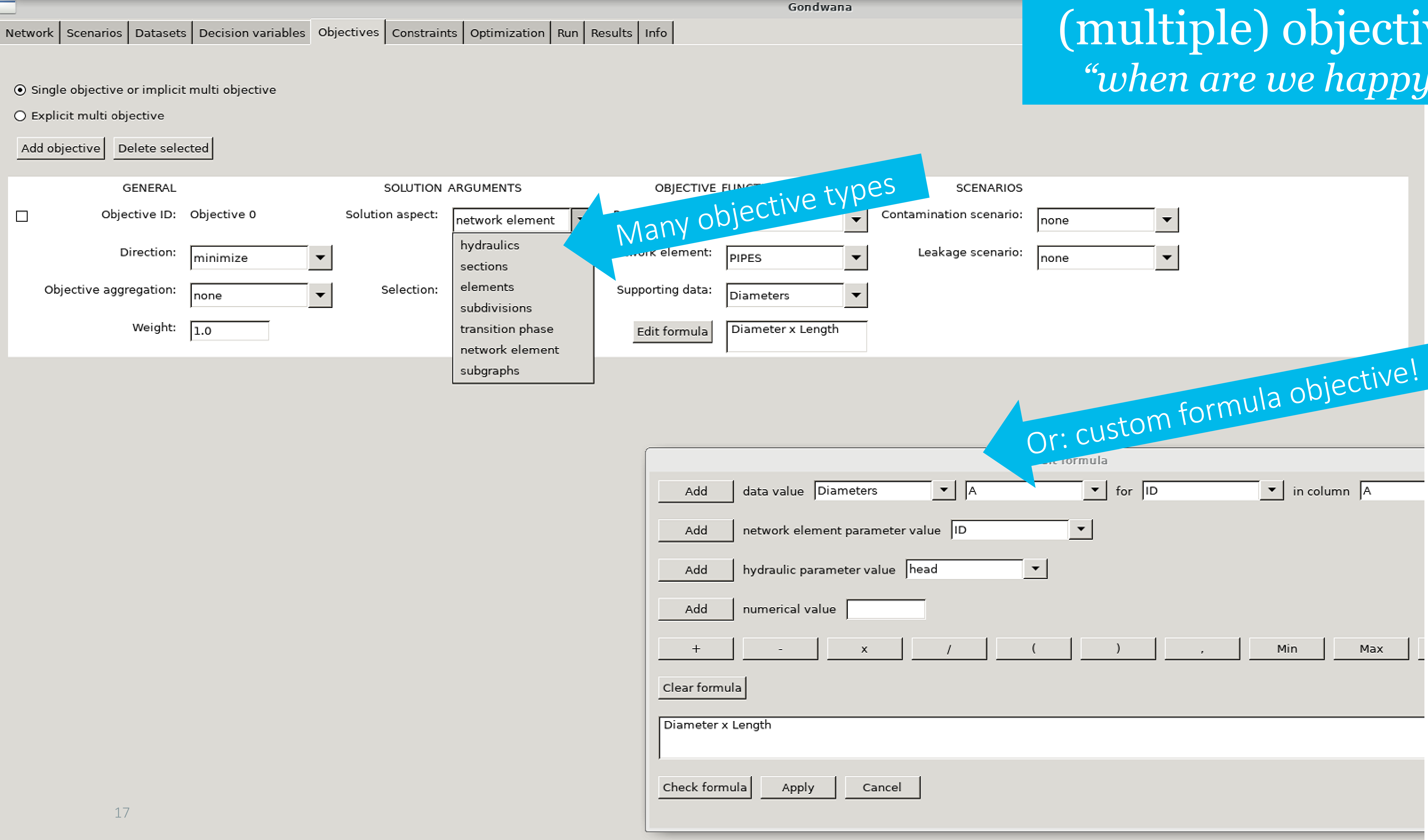
e.g.: those diameters

e.g.: that selection

As flexible as possible, e.g.:

- *"Change any parameter (diameter, status, …) of selected pipes, chosen from list"*
- *"Divide selected junctions into a number of clusters (DMA's)"*
- *"Assign a 'sensor-status' to a number of junctions in the network"*
- …

(multiple) objectives
"when are we happy?"



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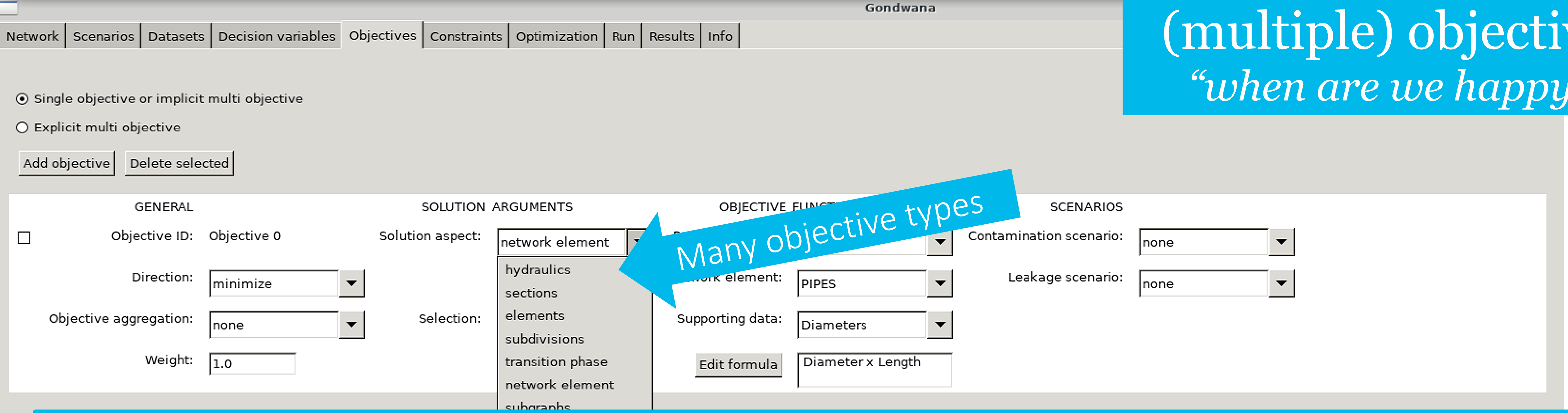
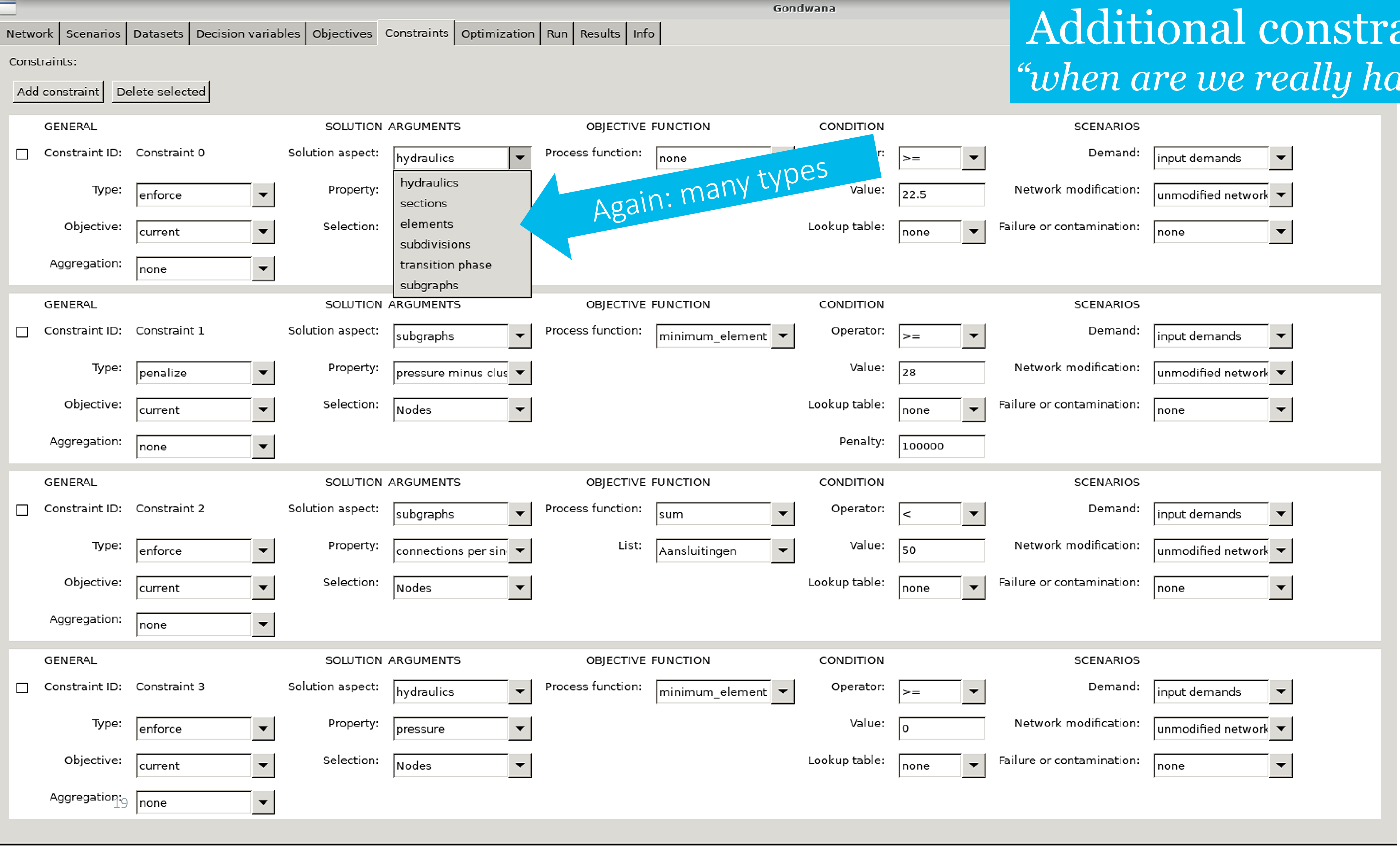


As flexible as possible, e.g.:

- [network element properties] *“minimize the volume of the selected pipes”*
- [network topology] *“maximize the percentage of the network that is branched”*
- [hydraulics] *“minimize the residence times in the selected part of the network”*
- [custom equations]

Additional constraints

“when are we really happy?”



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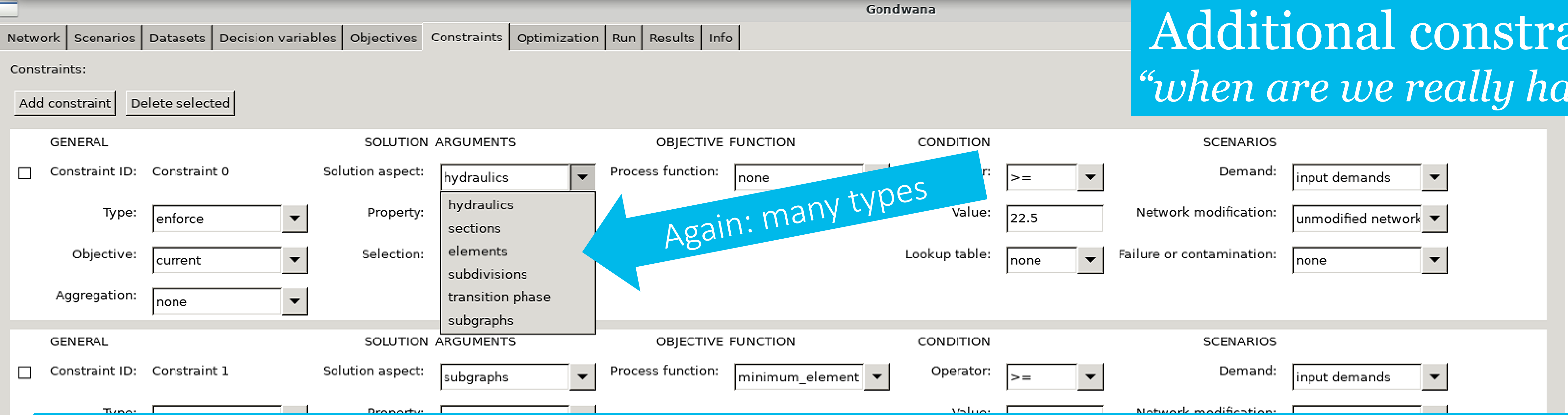
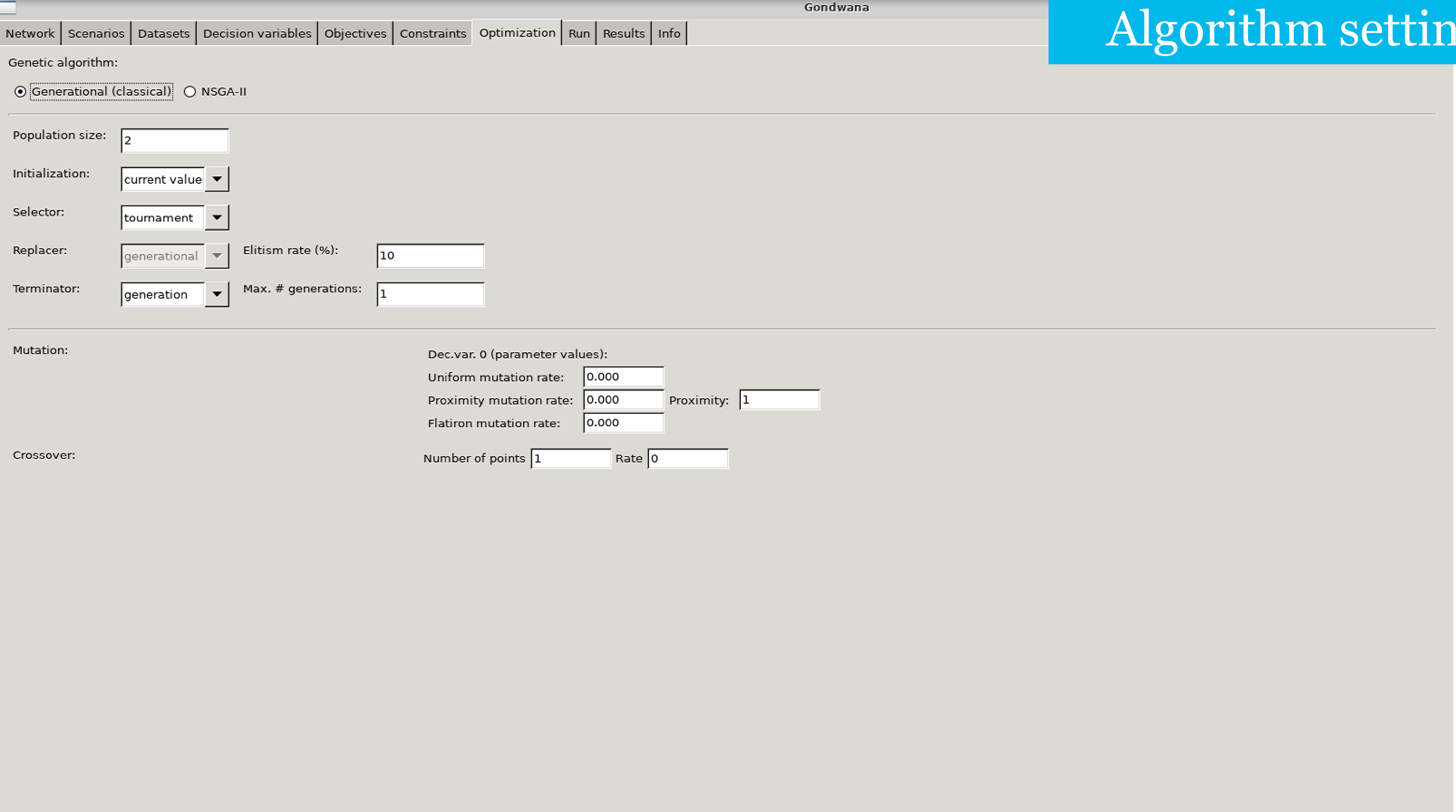


As flexible as possible, e.g.:

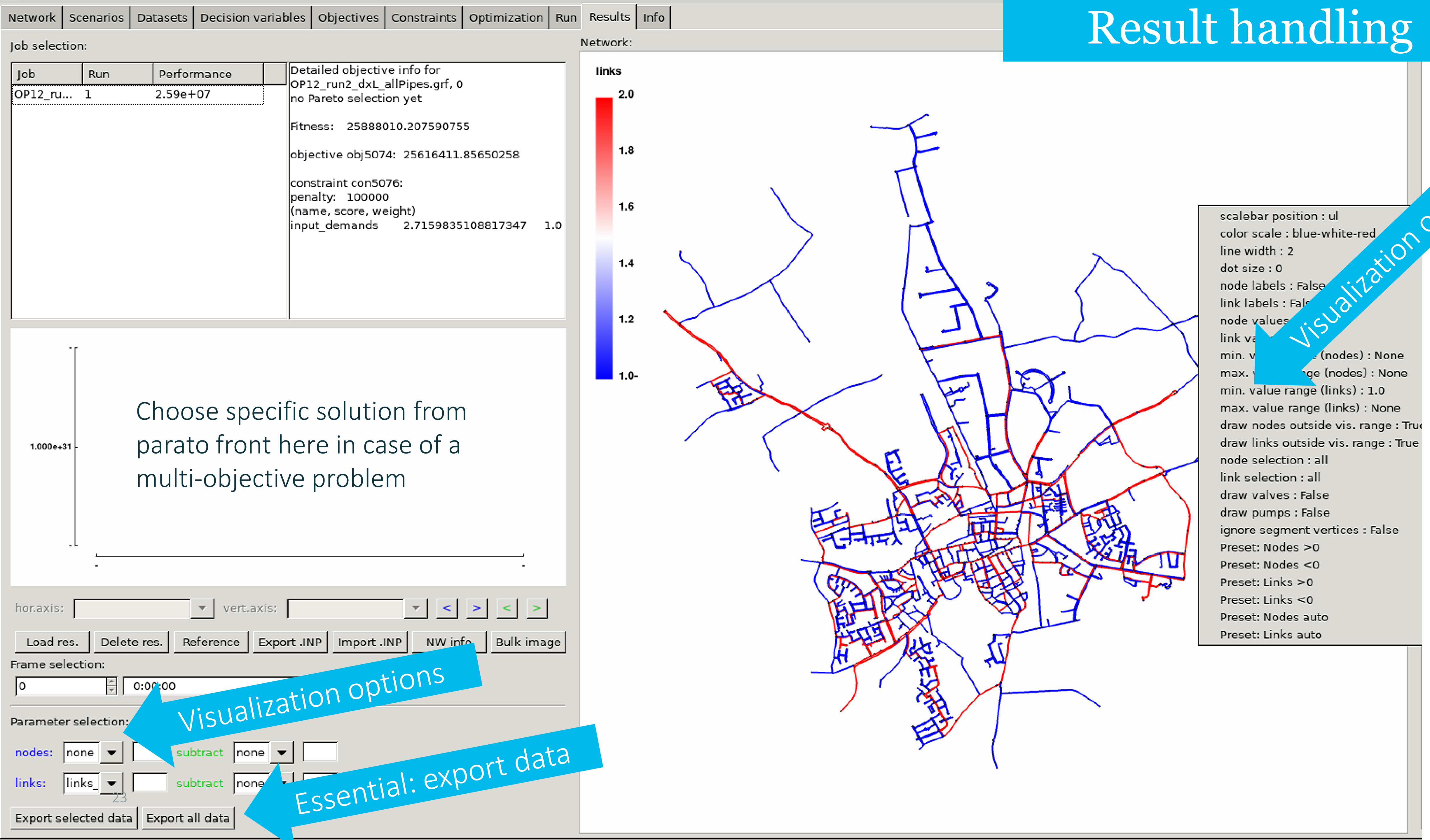
- *“branched parts of the networks can’t supply more than 50 connections”*
- [scenarios] *“these junctions should have >230 kPa, even when either of these pipes are closed”*
- …

Algorithm settings



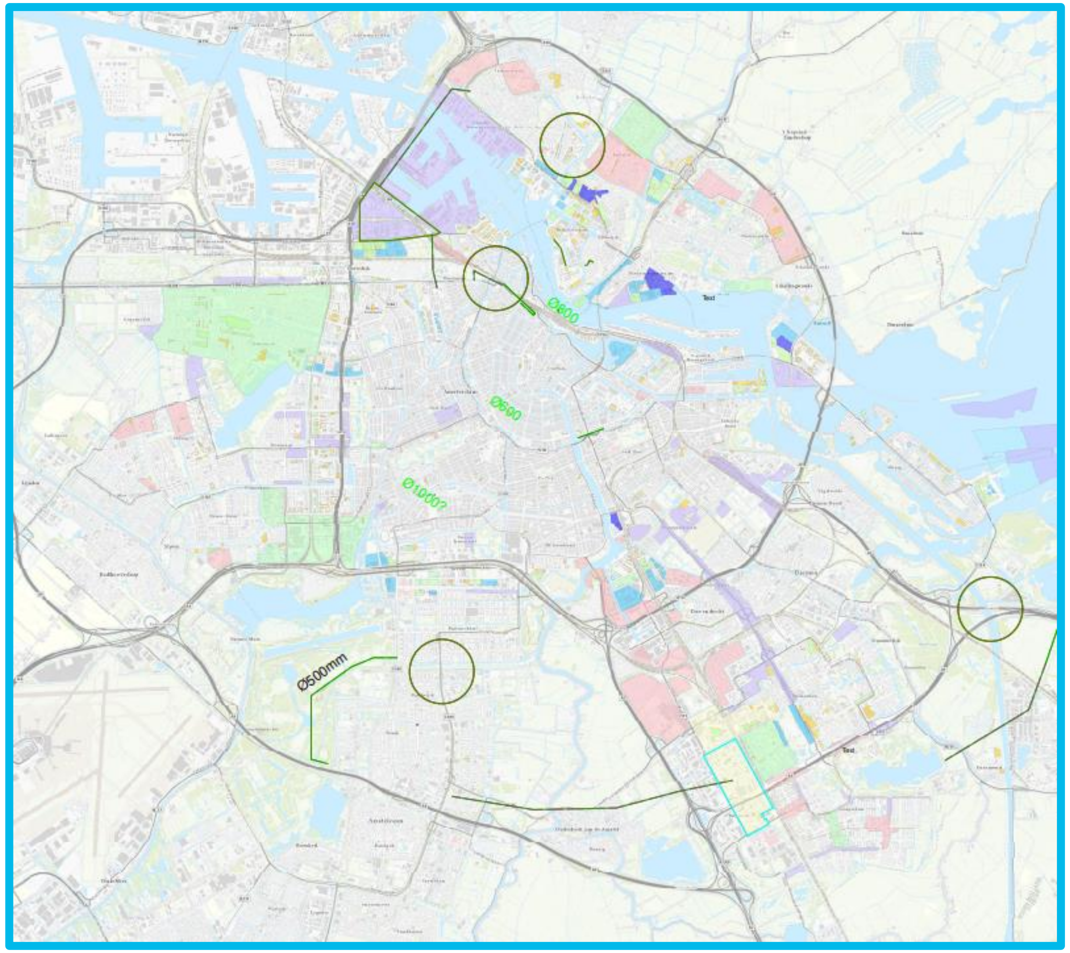
Task management

Result handling



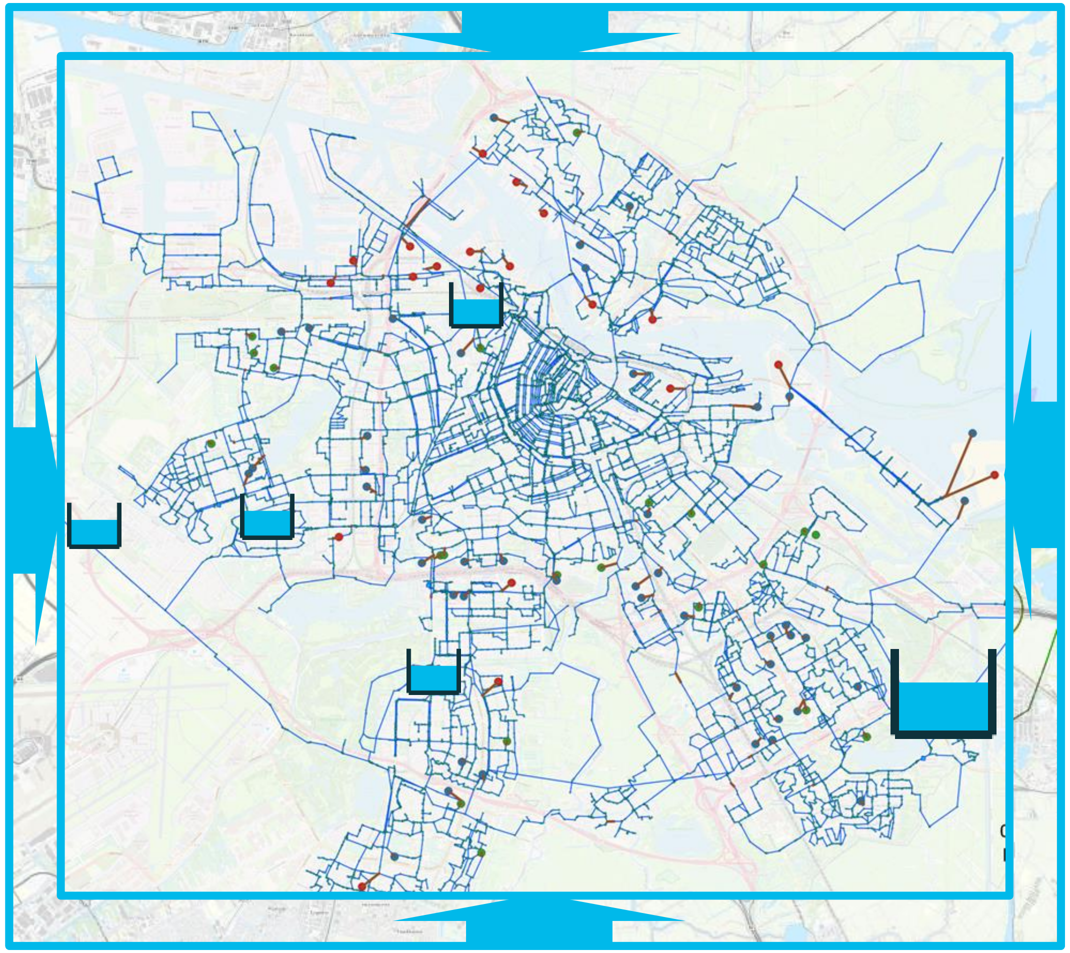
Example of application: Growth of Amsterdam

“Short term” (10 y) replacement plan

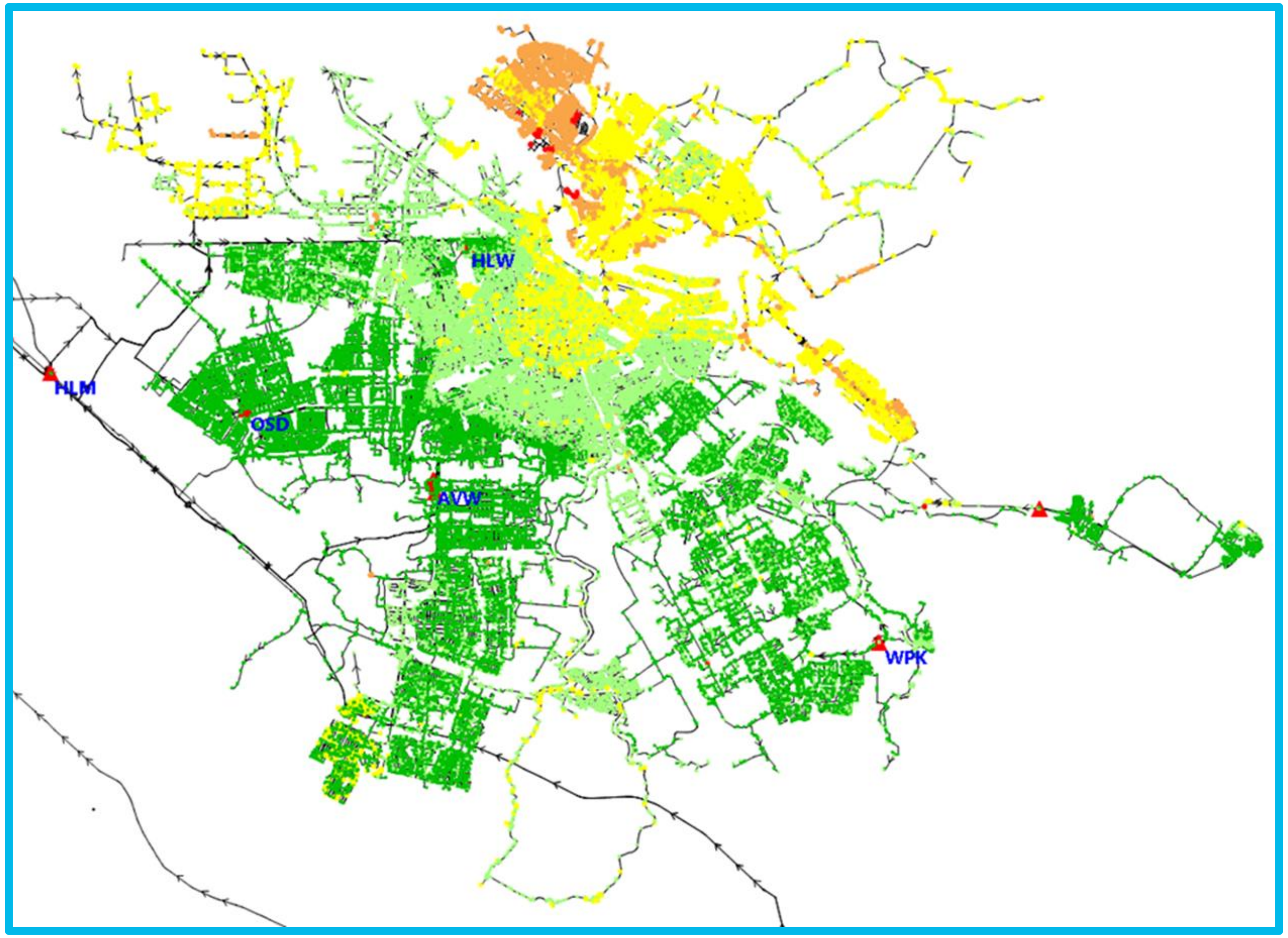


Expansion plans of the municipality of Amsterdam

“Short term” (10 y) replacement plan

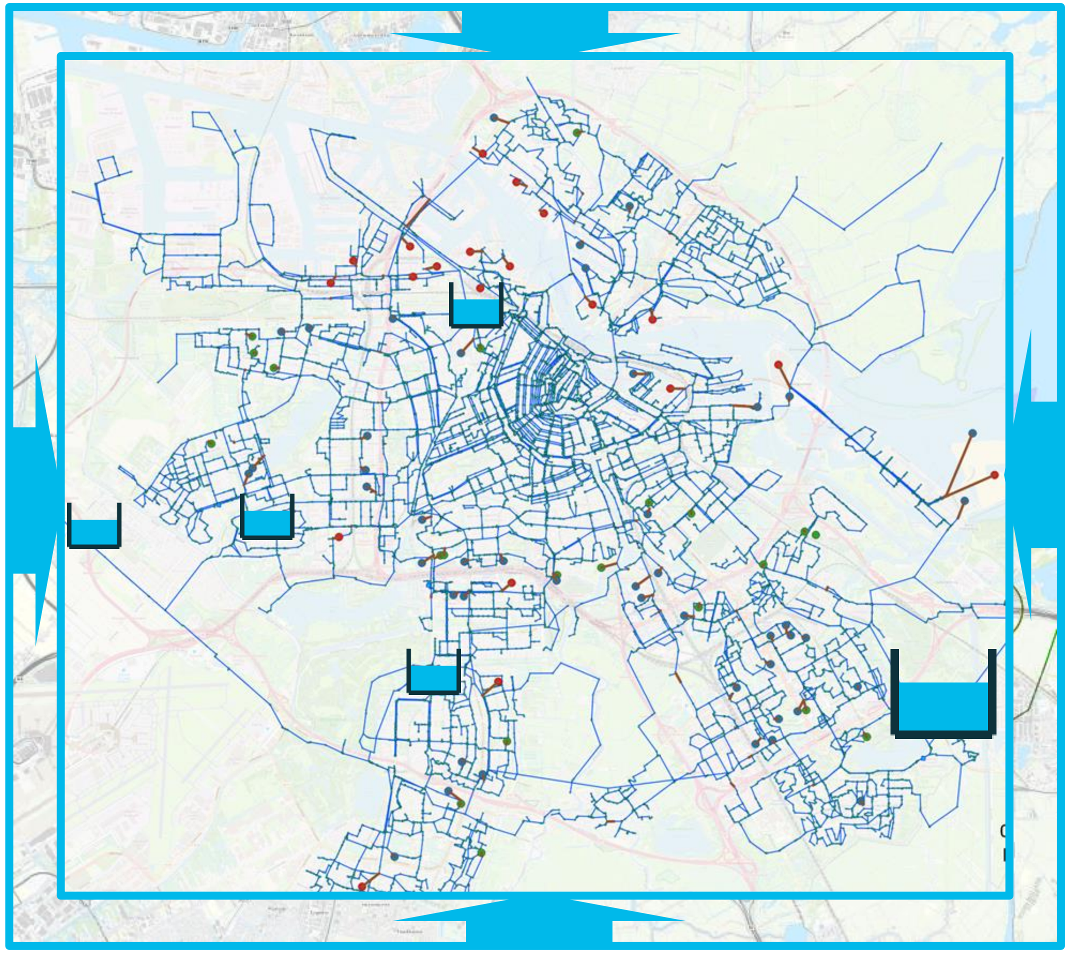


2 Modeled expansion plans of the municipality

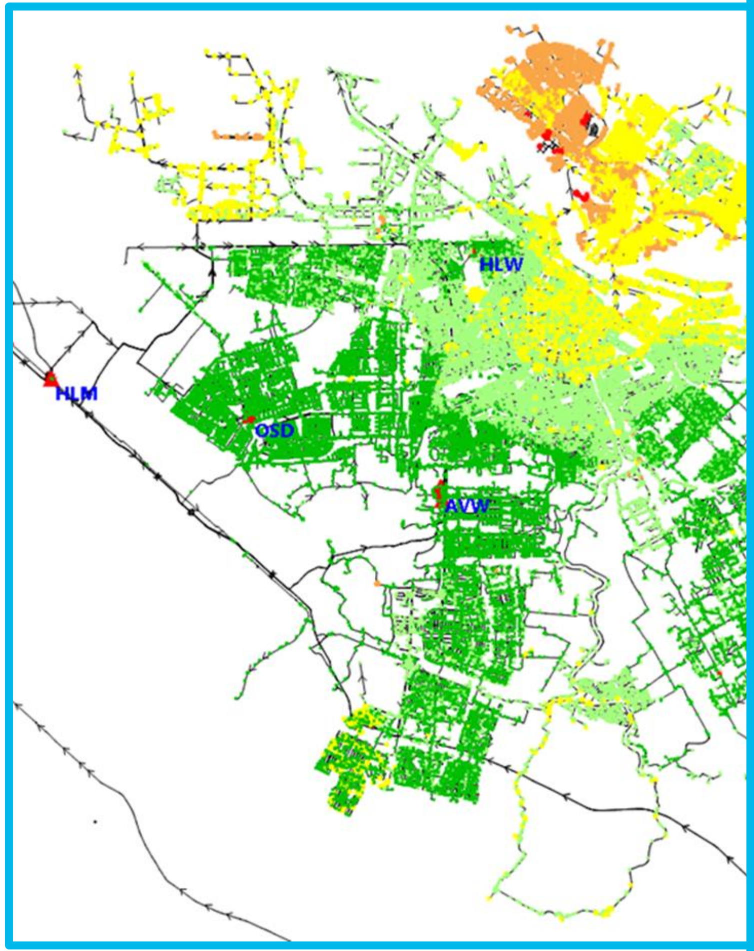


Resulting pressure issues in ~2030 (and getting worse)

“Short term” (10 y) replacement plan



[2]Modeled expansion plans of the municipality



Resulting pressure issues in ~20

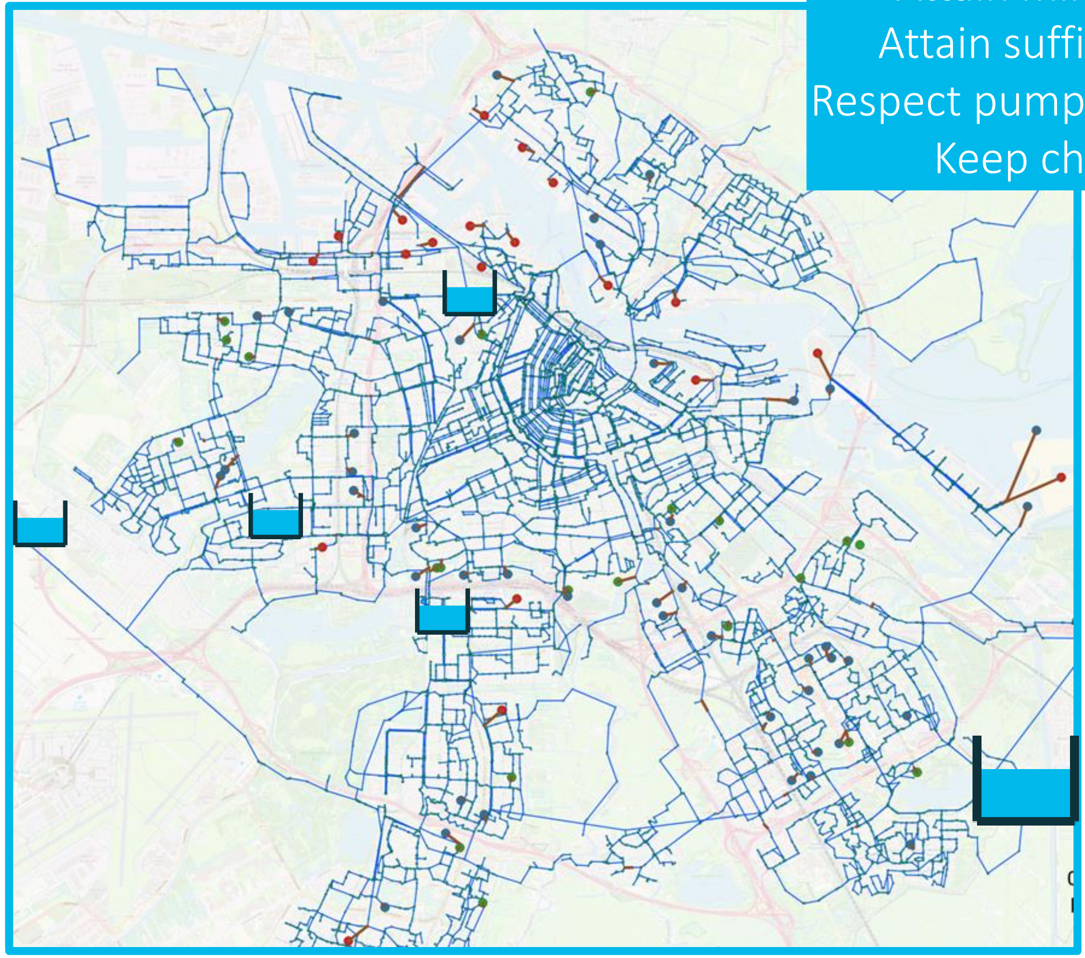
…

Moreover: insufficient redundancy vs. calamities

“Short term” (10 y) r

Optimization problem definition

Try adding new pipes
Try enlarging existing pipes
Try placing new pumping station
~
Attain minimum pressures
Attain sufficient redundancy
Respect pumping station capacities
Keep changes minimal



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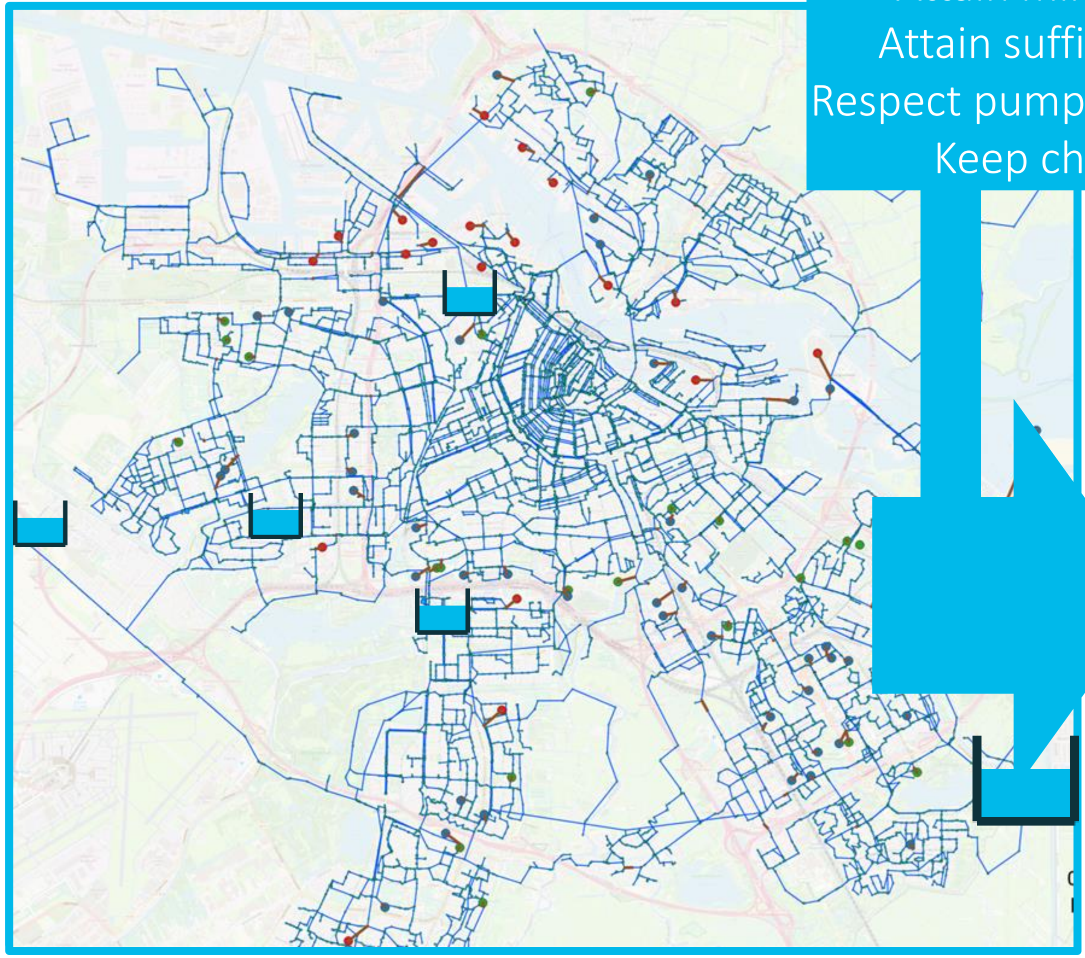

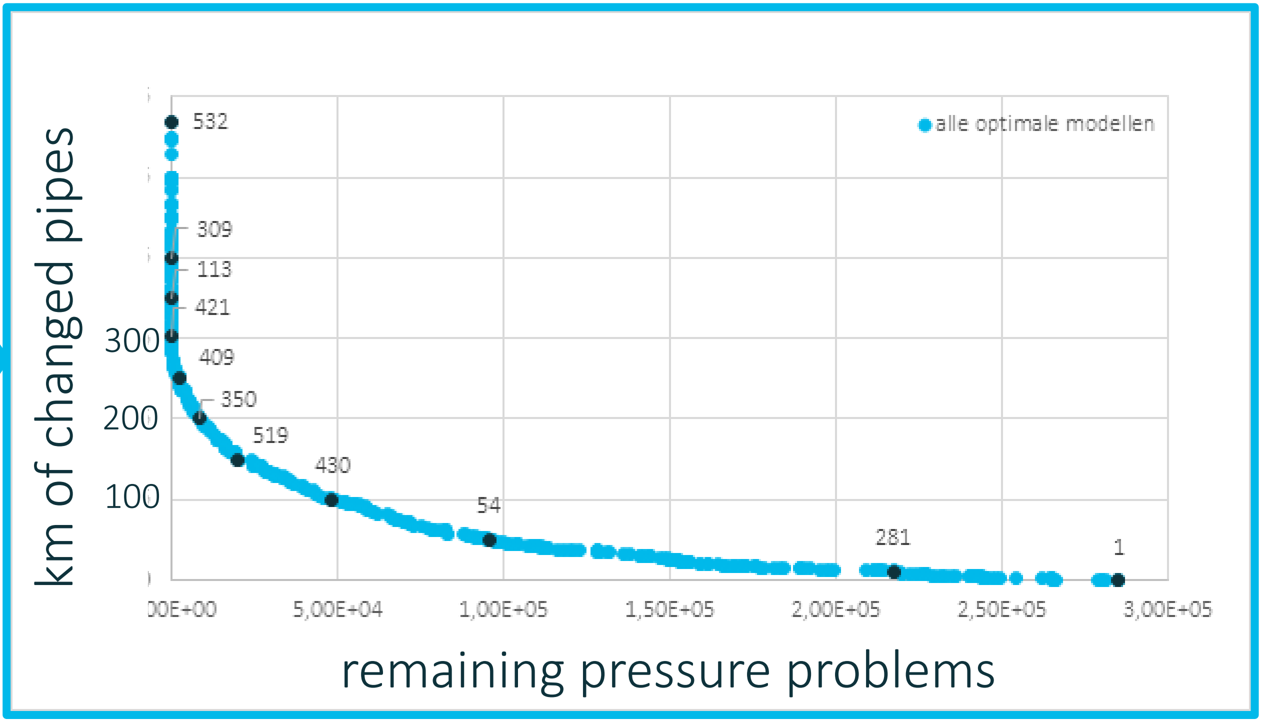

Pareto front showing Waternet’s most efficiënt options

“Short term” (10 y) r

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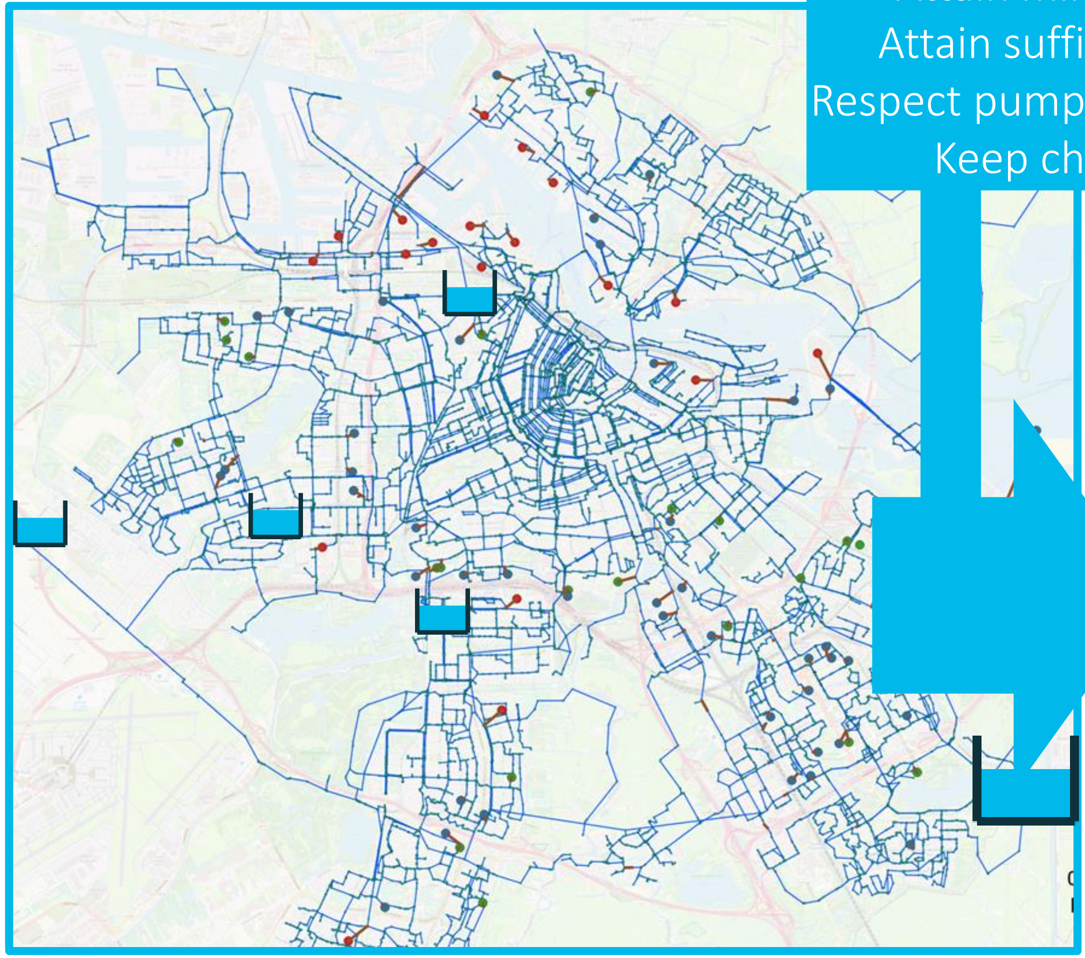
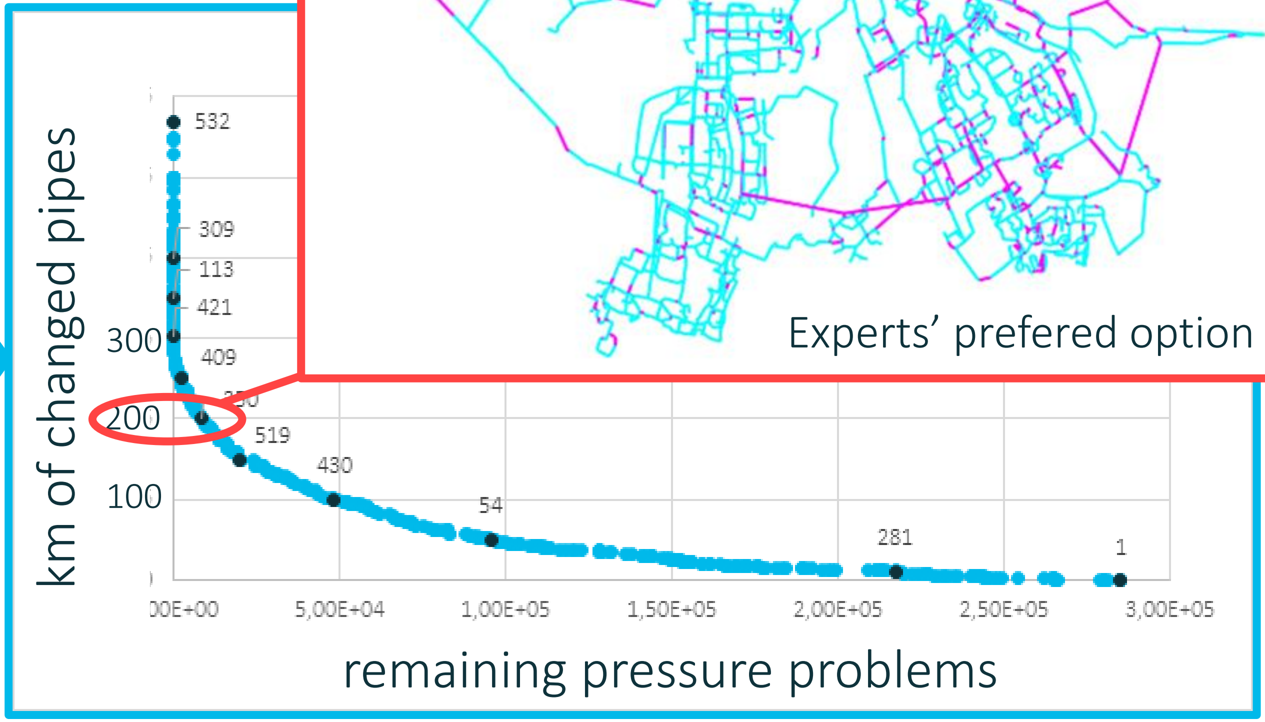
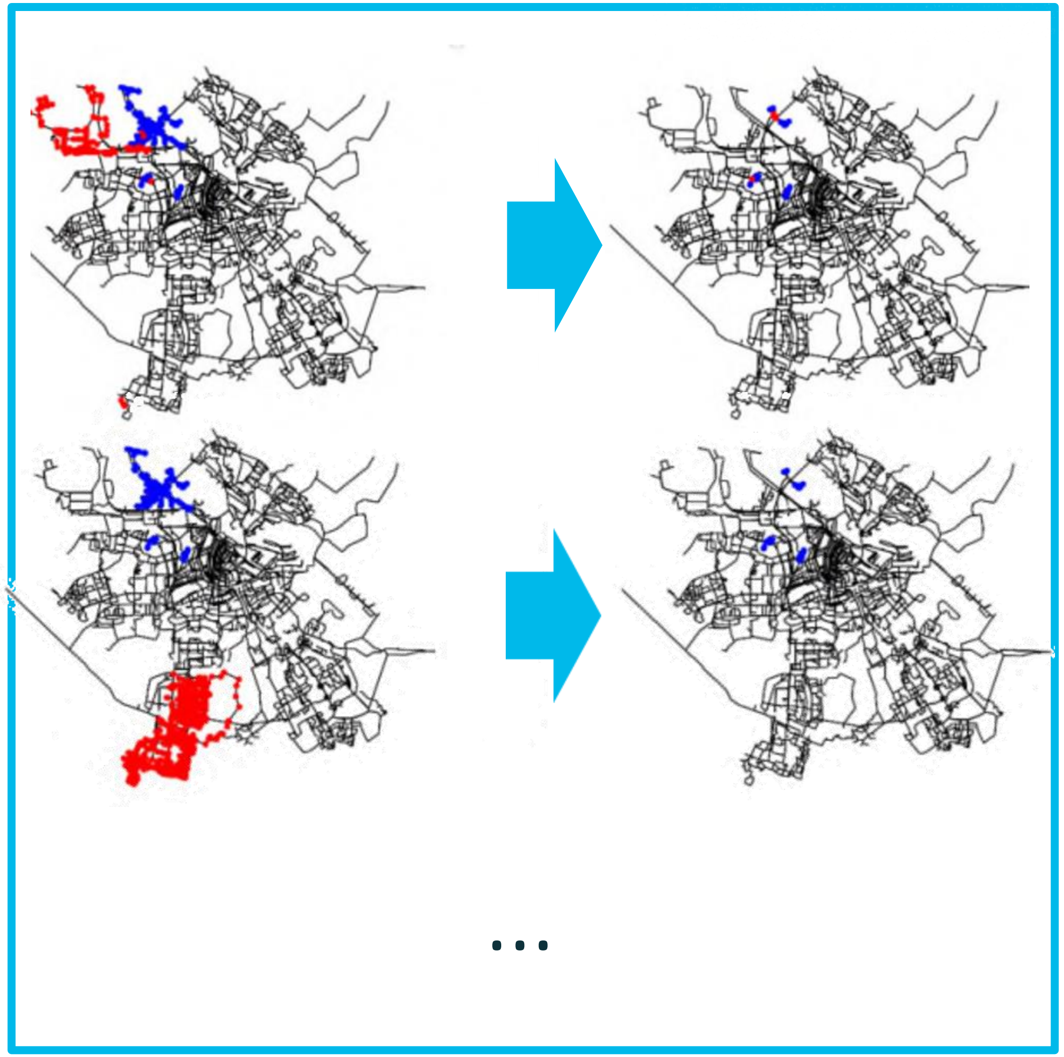




Pareto front showing Waternet’s most efficiënt options

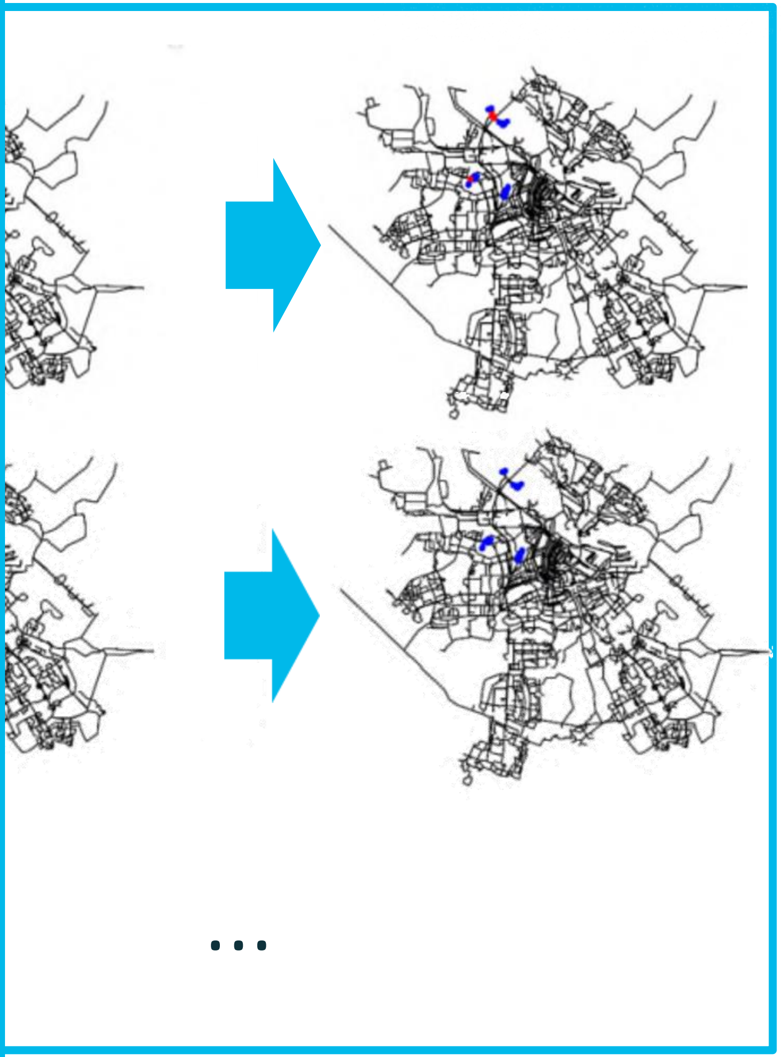
“Short term” (10 y) replacement plan



"Short term" (10 y) replacement plan

Main outcomes for Waternet:

- Quantitative insight in the size of the solution needed
- Input for first no-regret replacement decisions
- Input for discussion with management on budgets
- Input for strategic discussion with municipality
- Very easy to further explore other solutions



Success factors in these types of applications

Utility experts take an active role in iterative problem formulation

1 - insight in system

2 - insight in question

3 - trust in algorithm

4 - trust in answer

Eight years after the first research projects with Gondwana:

- utilities ask if optimization can help with …
- first utility with the desire to train own experts in use of Gondwana

Algorithm choice and computational speed:

- far less important than you might assume, but becomes an issue for 'urgent questions'

Thank you for your attention

KWR

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@KWR_Water

KWR

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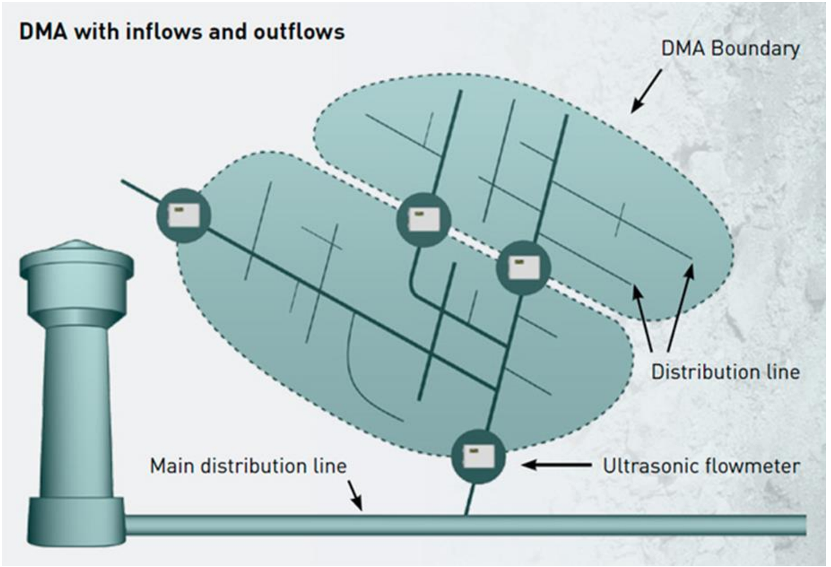
DMA sensor network design

How to subdivide a network into DMA’s?

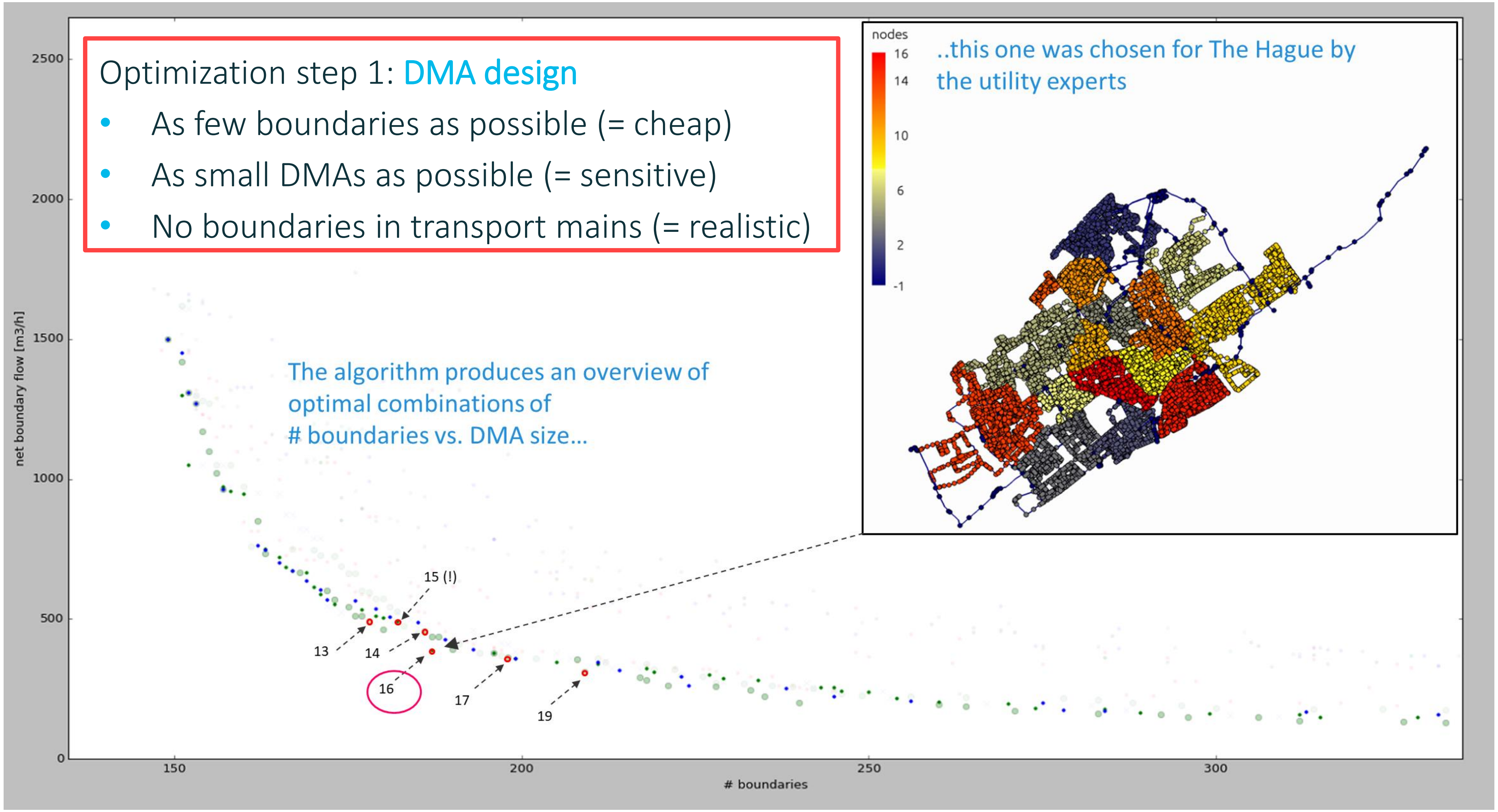
- DMA’s: subnetworks with flow meters on the boundaries
- DMA’s provide insight in distribution (leakage, flow, ...)
- Historically, DMA’s not used in NL
- Many network changes required to create DMA’s now (closing pipes, installing flow meters, ...)
  - Expensive
  - Impact on hydraulics and topology

District Metered Area



How do I get as many DMA’s as possible with as few network changes possible?

DMA sensor network design



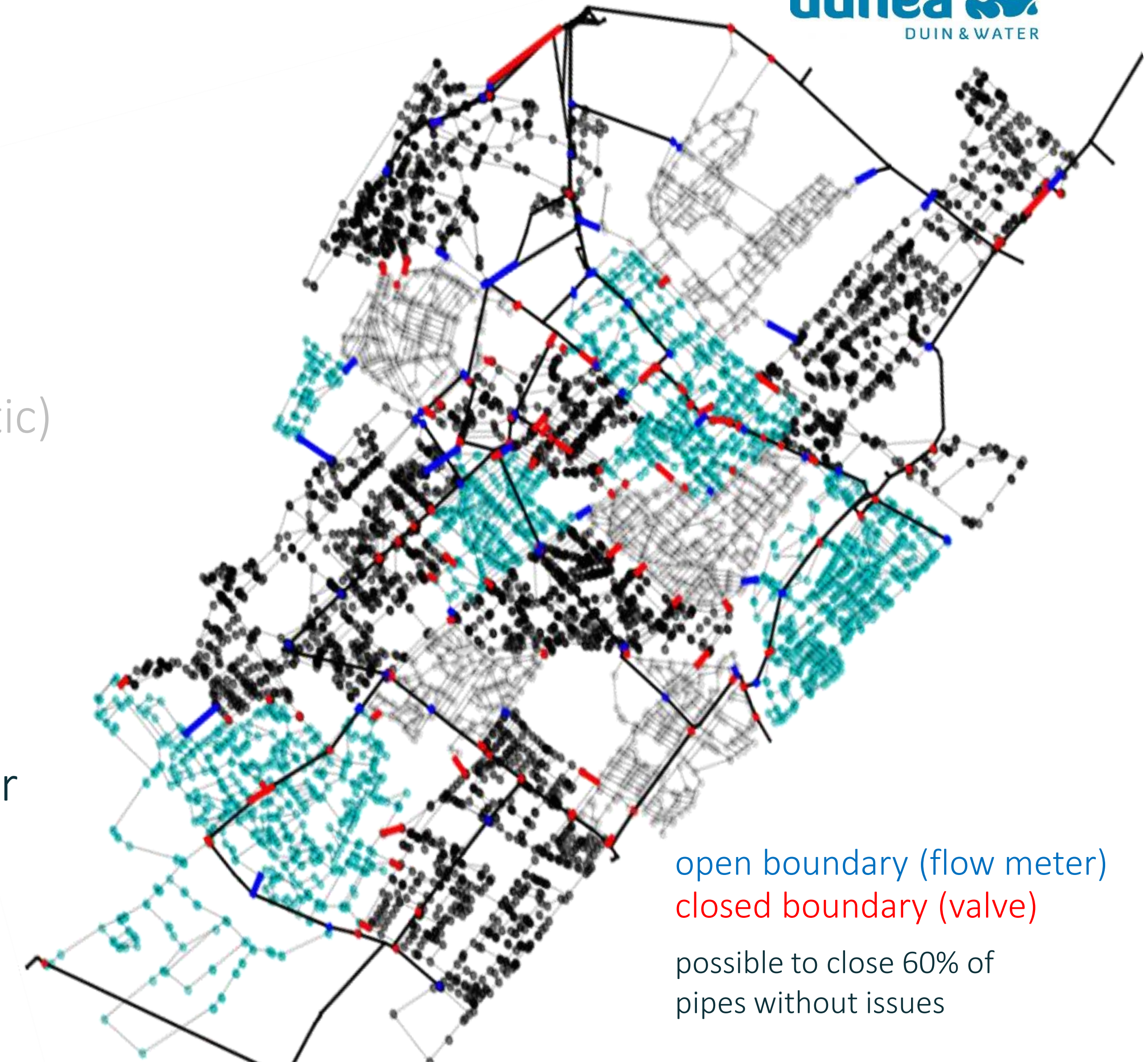
DMA sensor network design

Optimization step 1: **DMA design**

- As few boundaries as possible (= cheap)
- As small DMAs as possible (= sensitive)
- No boundaries in transport mains (= realistic)

Optimization step 2: **boundary configurations**

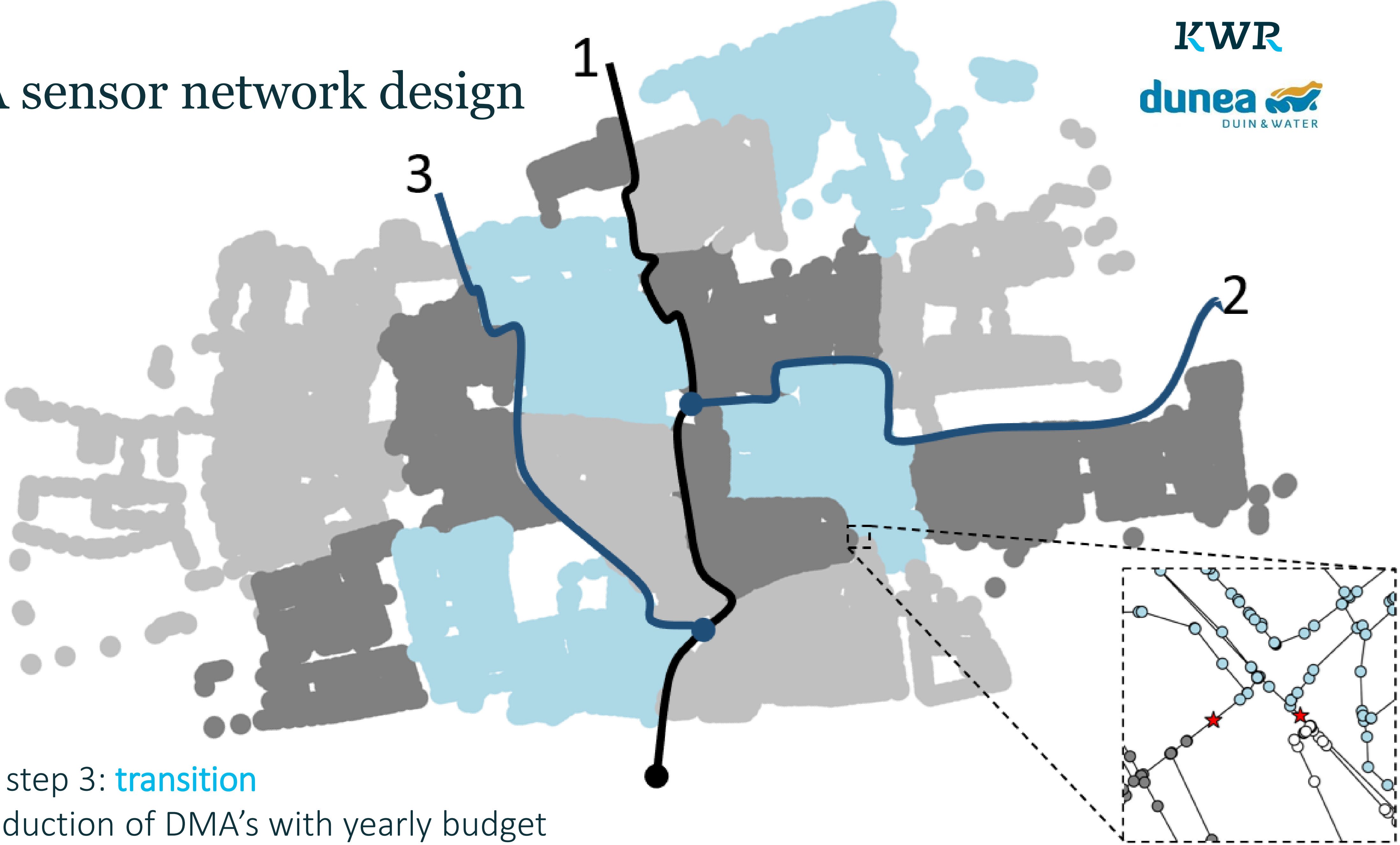
- Close as many boundaries as possible (cheaper, but impact on hydraulics, so…)
- Maintain pressure service level (= customer satisfaction)
- Maintain security of supply (= law)



open boundary (flow meter)
closed boundary (valve)

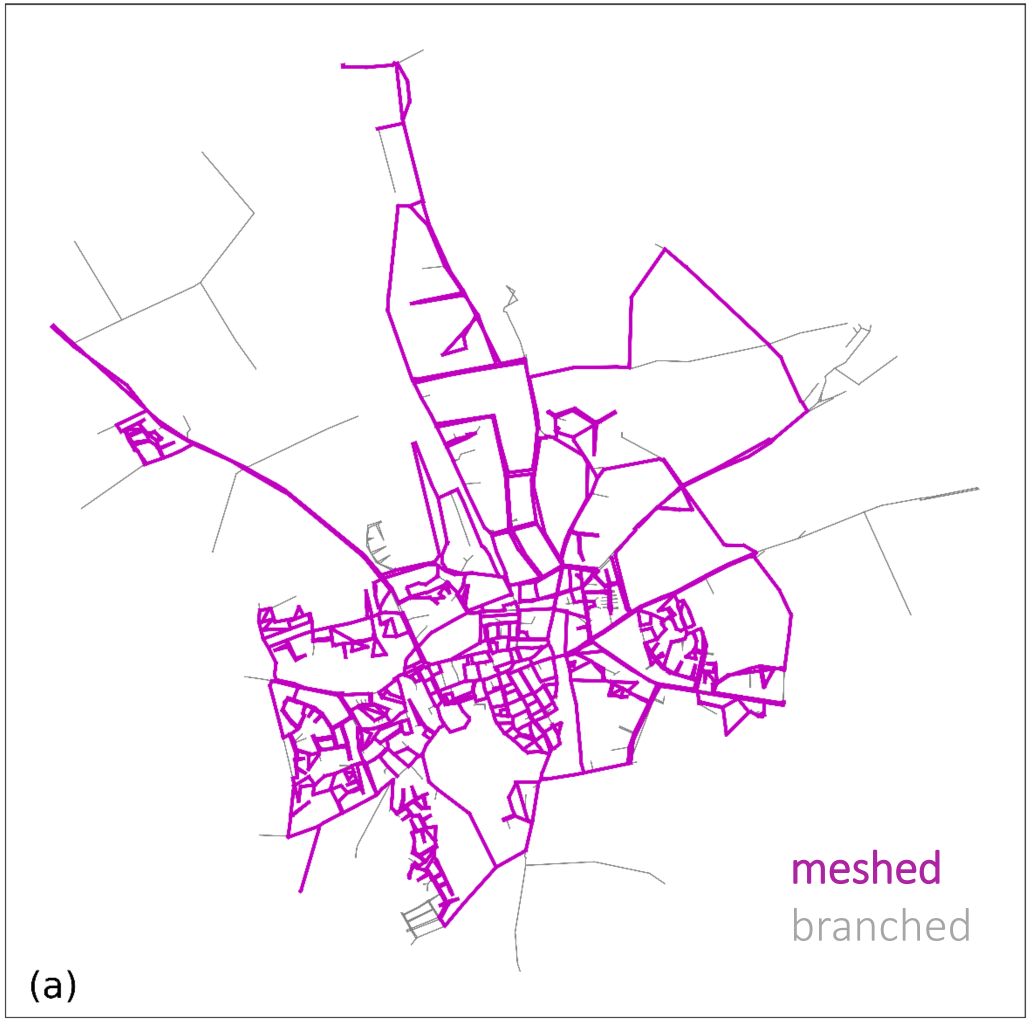
possible to close 60% of pipes without issues

DMA sensor network design



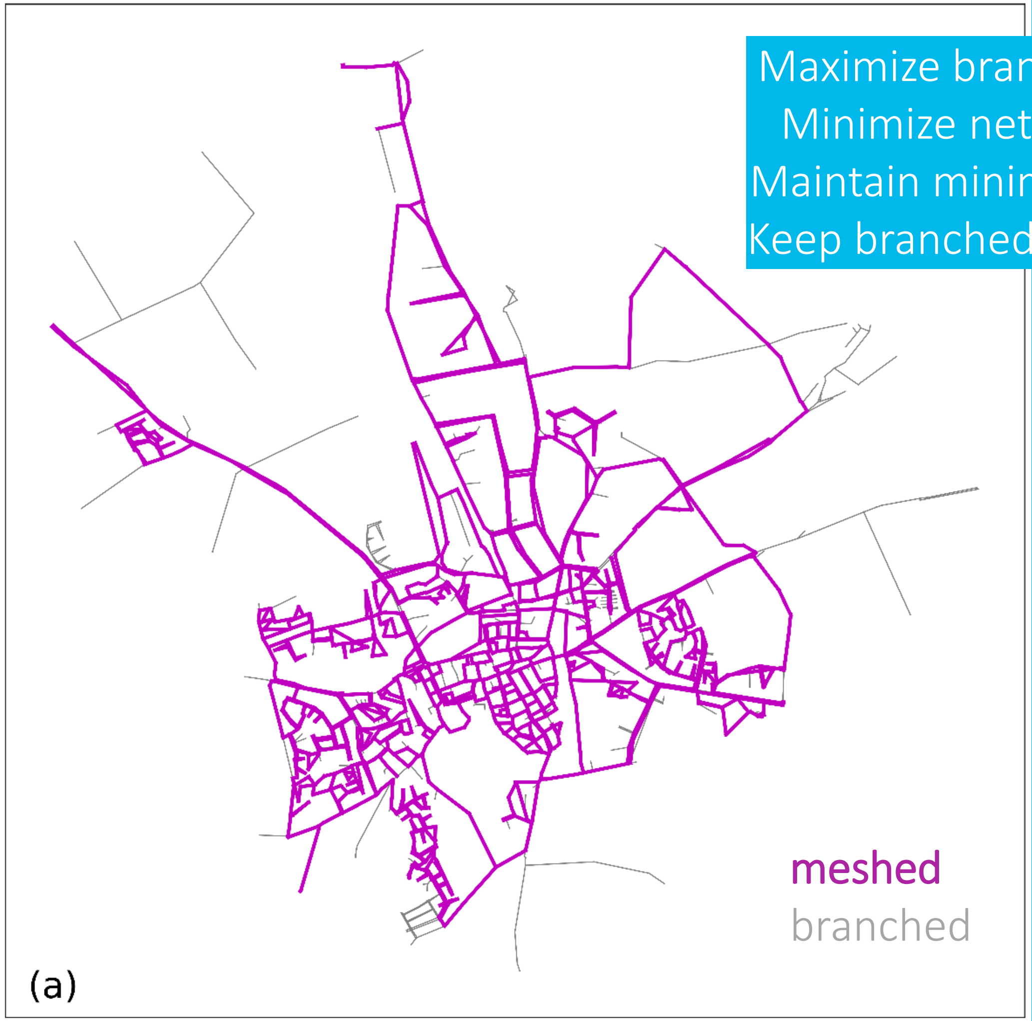
Optimization step 3: transition
Gradual introduction of DMA's with yearly budget

Long term design & water quality



Networks in Flanders typically are highly meshed, with large redundancy but also with large residence times and sediment issues

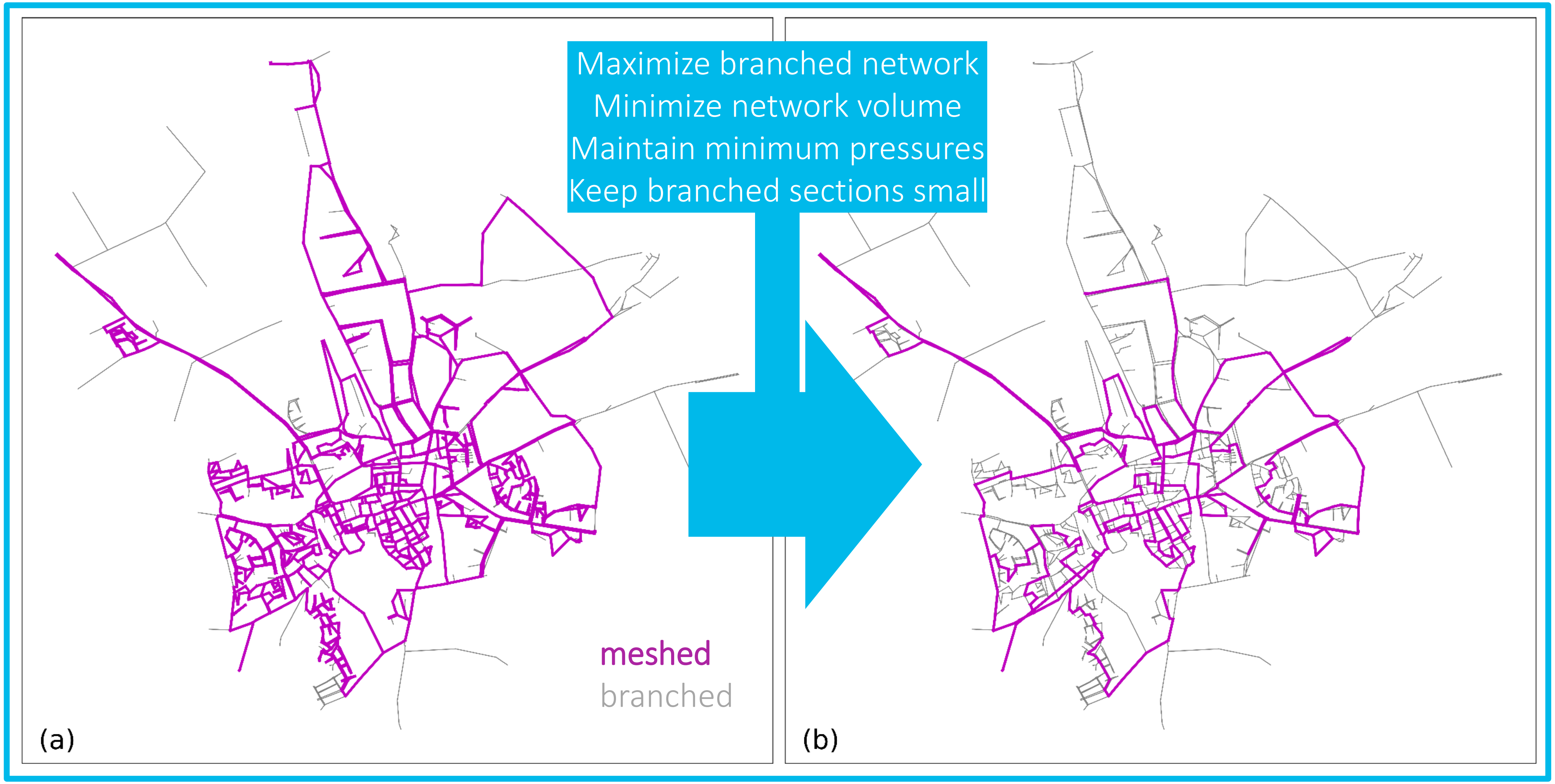
Long term design & water quality



Maximize branched network
Minimize network volume
Maintain minimum pressures
Keep branched sections small

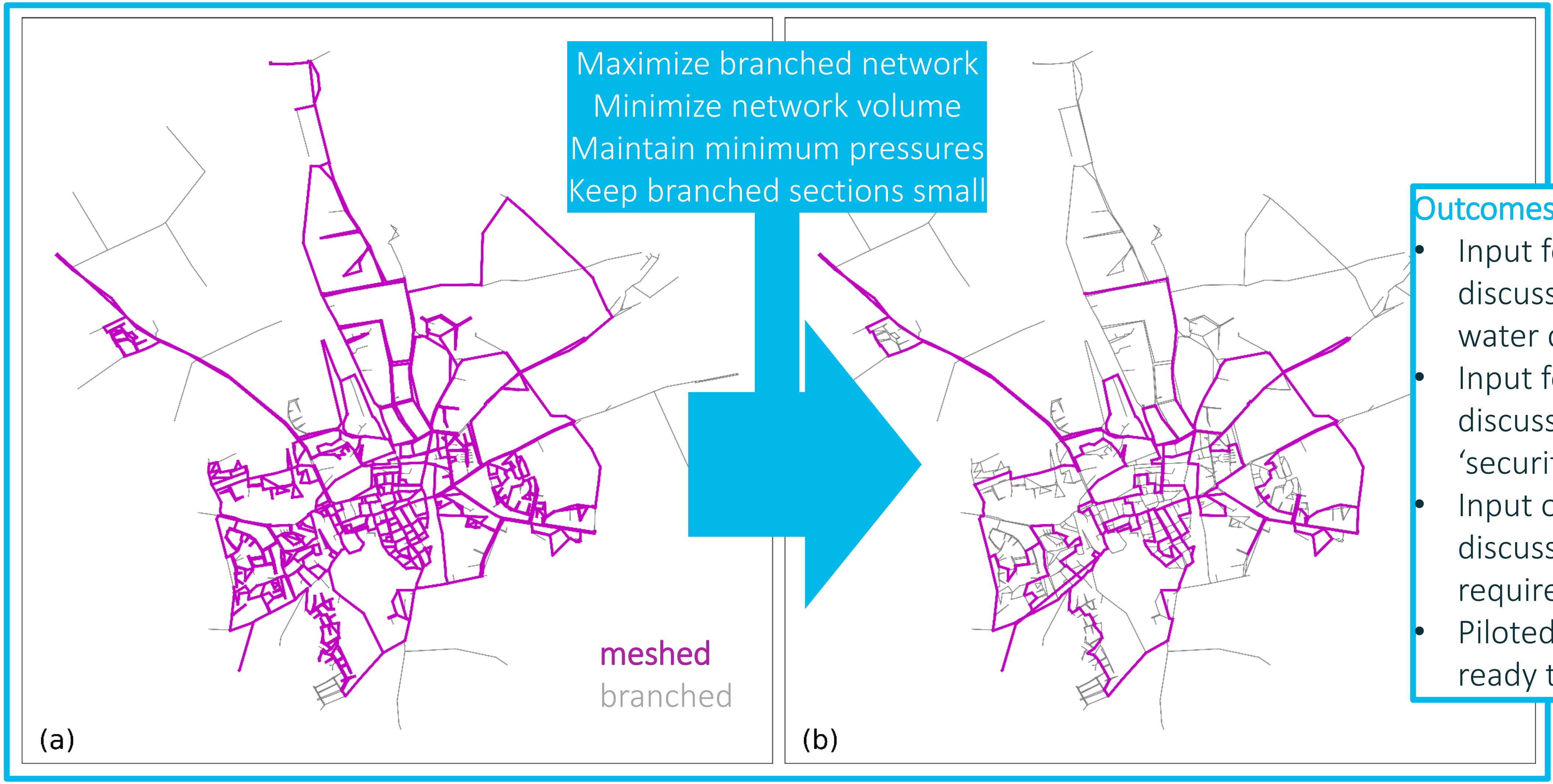
Optimization problem to create a network with a 'Dutch structure' (self cleaning design), maintaining sufficient reliability of supply.

Long term design & water quality



About 66% of the network length can be converted from a meshed to a branched structure

Long term design & water quality



Outcomes for De Watergroep:

- Input for strategical discussion on designing for water quality
- Input for strategical discussion on designing for ‘security of supply’
- Input on strategical discussion on fireflow requirements
- Piloted design approach, ready to roll out

Leak Detection Using Autoencoders

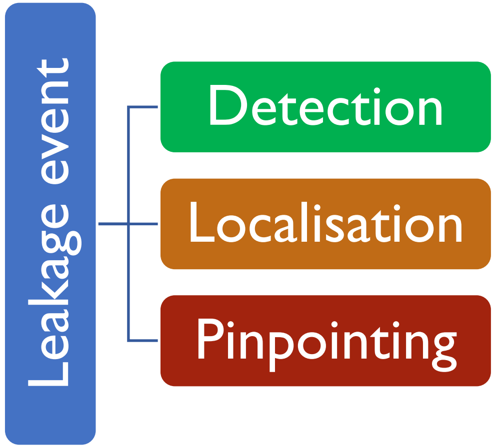
Prasanna Mohan Doss (NTNU)
Magnus Renslo Totland (NTNU)
Franz Tscheikner-Gratl (NTNU)
Marius Møller Rokstad (NTNU)
David Steffelbauer (KWB, Berlin)

Water Distribution Networks (WDNs)

- Network of interconnected pipes, valves, pumps, reservoirs and tanks
- Main objective: Deliver potable water to consumers 24x7reliably
- Challenges: ***Leakages***, Scheduling of network operations (monitoring & control)

→ In Norway, ~ 30% loss in leakages!

Leakage Detection and Localization (LDL)



Finding that leak(s) has occured

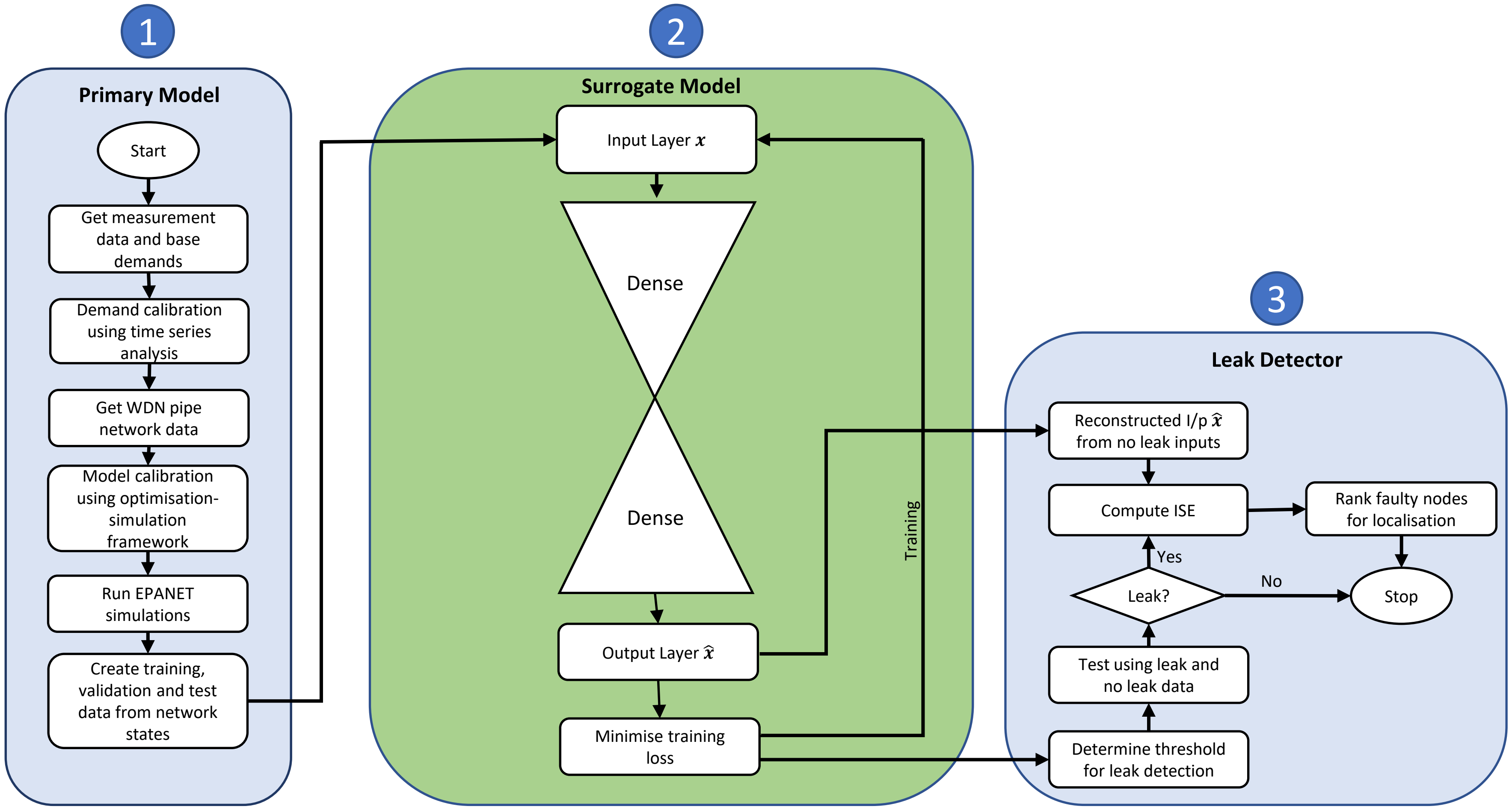
Approximating the location

Exact position of leak

→ Difficult for low flow leaks! (<1 LPS)

} Measure of repair time

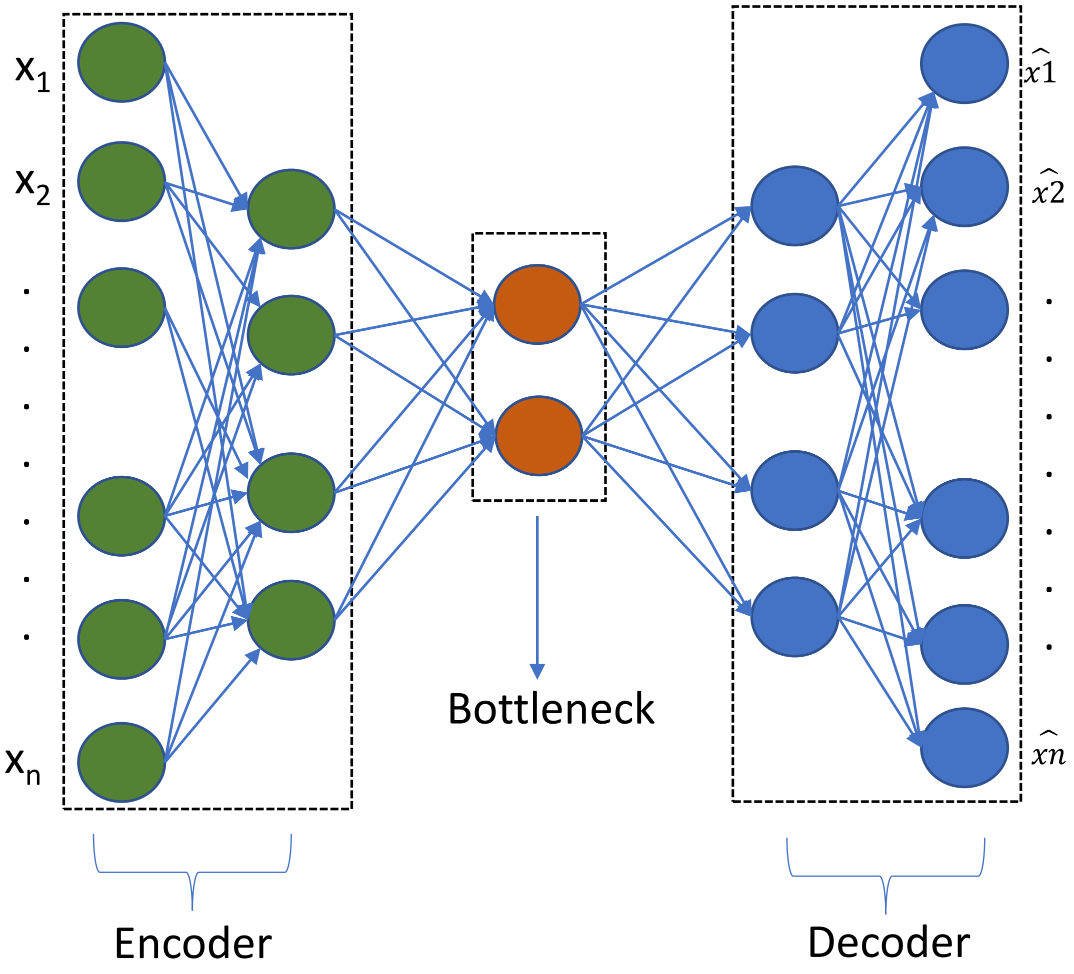
The three-step strategy in Leak Detection



Decoupling Hydraulics using Surrogate Modeling

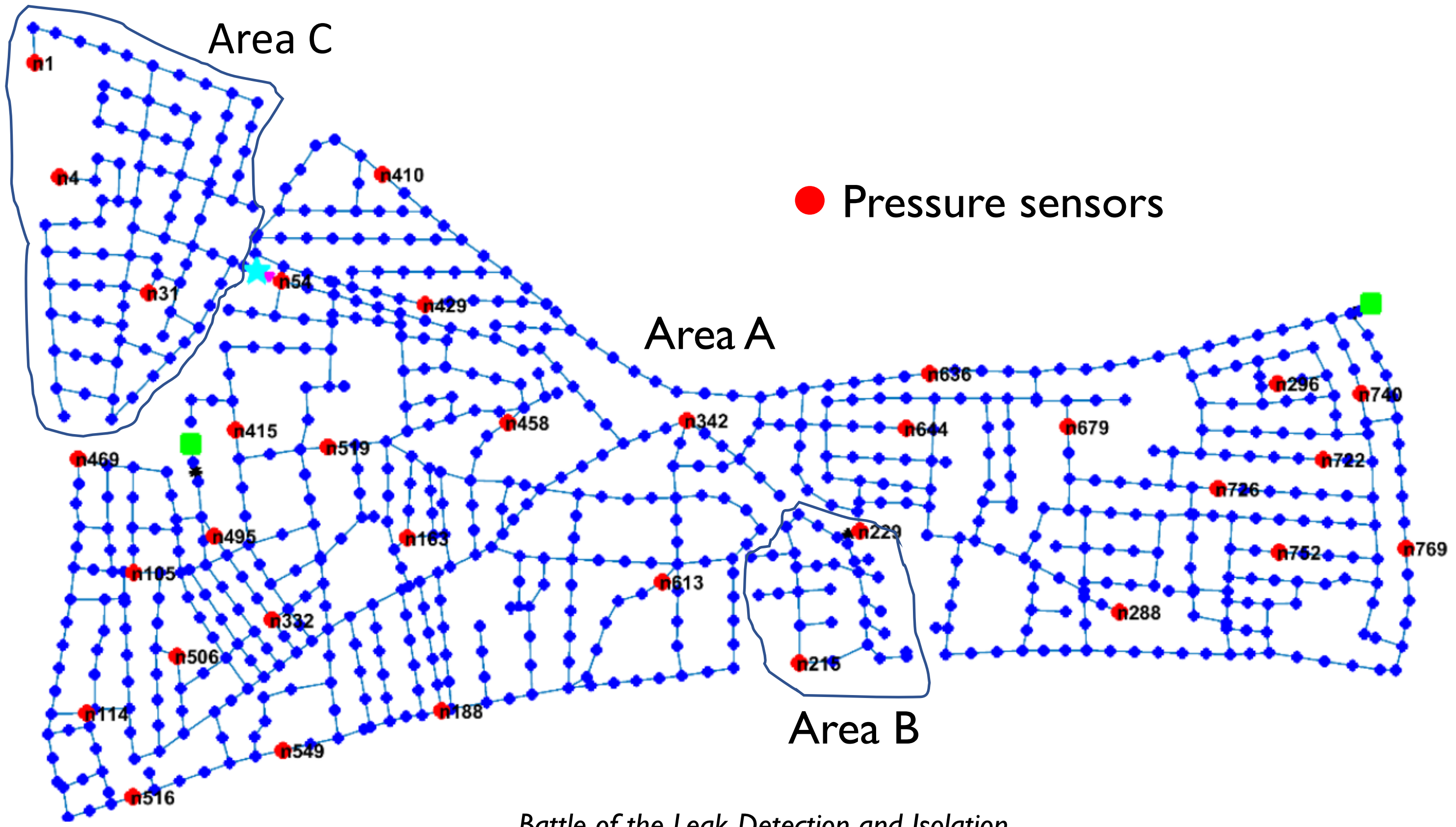
- In the first step, demand calibration and pipe roughness calibration is done using combination of time series modeling and optimisation framework.
- The 2nd and 3rd step involves the development of surrogate models using Artificial Neural Networks (ANNs).
- These surrogate models 'learn' to mimic physical changes in the target signals depending on the correlations among input signals and event(s) that causes changes in them.
- Encoder-decoder models are special class of unsupervised methods that are used to reconstruct input signals.
- In this work, two types of encoder-decoder models are tested on a synthetic WDN – a deterministic model and a generative model for LDL.

Autoecoders (AE) as surrogates for detection



- AEs are unsupervised ANNs that are used to learn 'encodings' efficiently.
- They perform non-linear dimensionality reduction at the bottleneck layer to preserve maximum useful information of input features.
- The outputs are approximated reconstructions of inputs – hence used for anomaly detection.

L-Town WDN Case Study



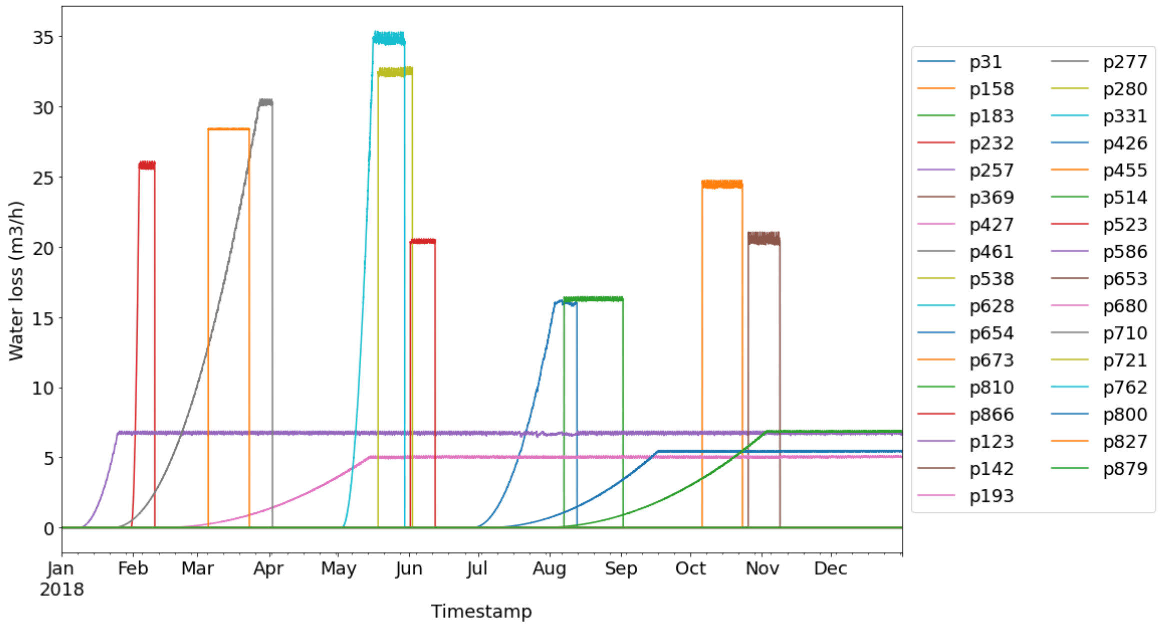
Battle of the Leak Detection and Isolation Methods (BattLeDIM) competition (Vrachimis et al., 2020)

Network Details:

- 782 nodes
- 905 pipes
- 2 Reservoirs
- 1 Tank and 1 Pump
- 3 DMAs
- 33 Pressure sensors

Dataset and Leak Scenarios

- Steady-state analysis is done using EPANET for two years 2018 and 2019 at 5-minute hydraulic timestep
- Two types of leaks are simulated at different times – Abrupt pipe bursts and slow increase incipient leaks

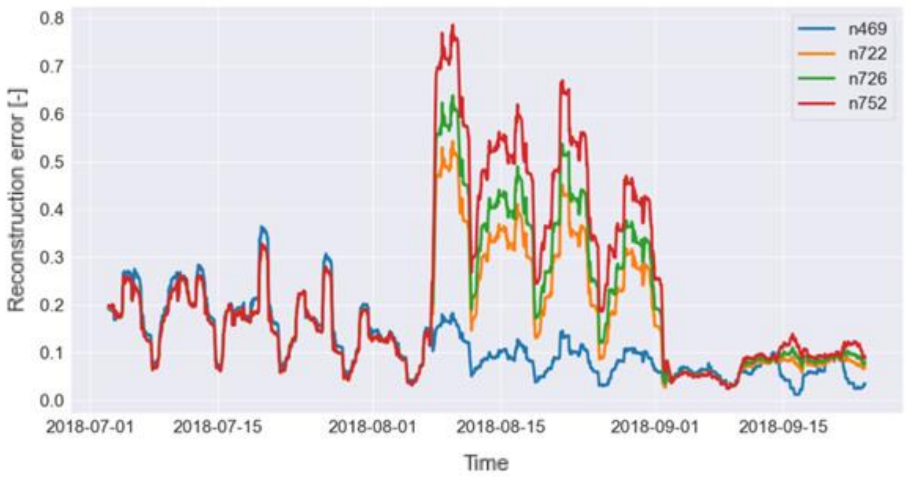


- A total of 33 leak leak scenarios were simulated in addition to normal operational state.
- All measurement locations and steady states are stored in a database for further analysis.

Results of AE as surrogates

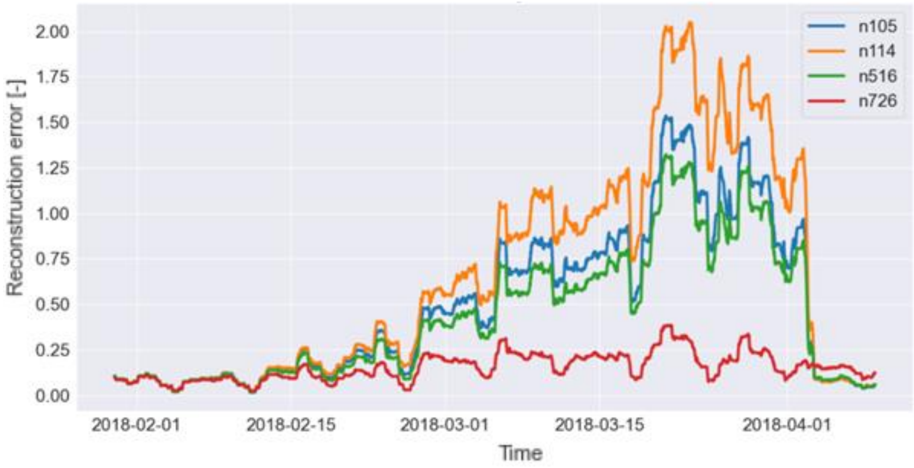
Autoencoder architecture	Autoencoder 6
Loss function	Mean square error
Activation function	Tanh
Optimizer	Adam
Learning rate	0.025
Epochs	2500
Batch size	750
Training interval	14 days
Validation interval	14 days
Testing interval	14 days

Quick burst leak at p183 (16.2 m3/hr)



Time to detect ~ 0.5 mins

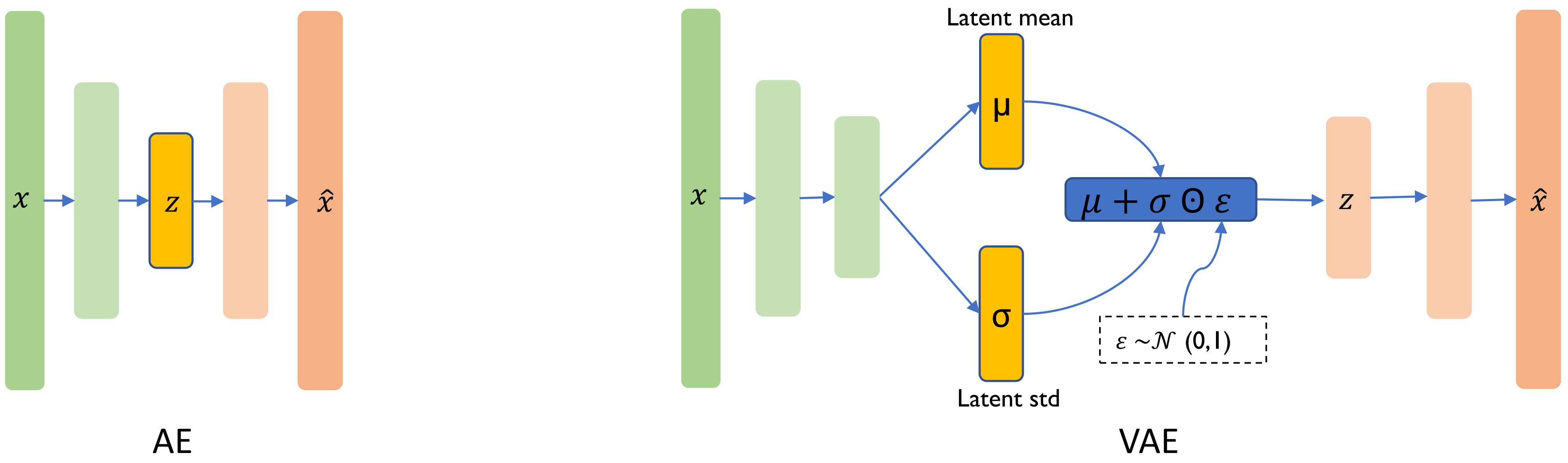
Incipient leak at p461 (4.28 m3/hr)



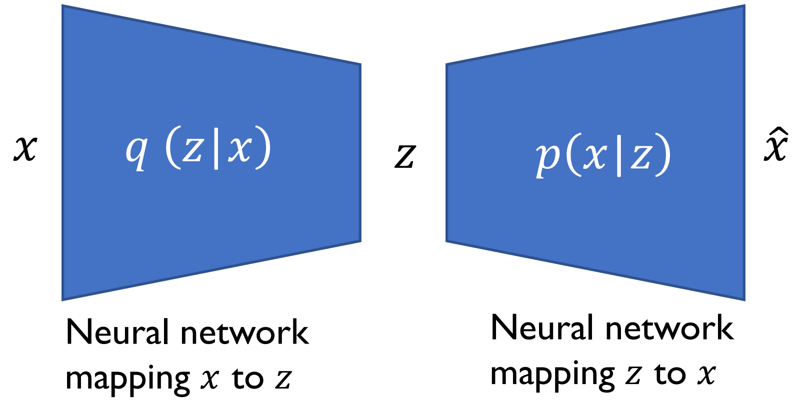
Time to detect ~ 22 hrs

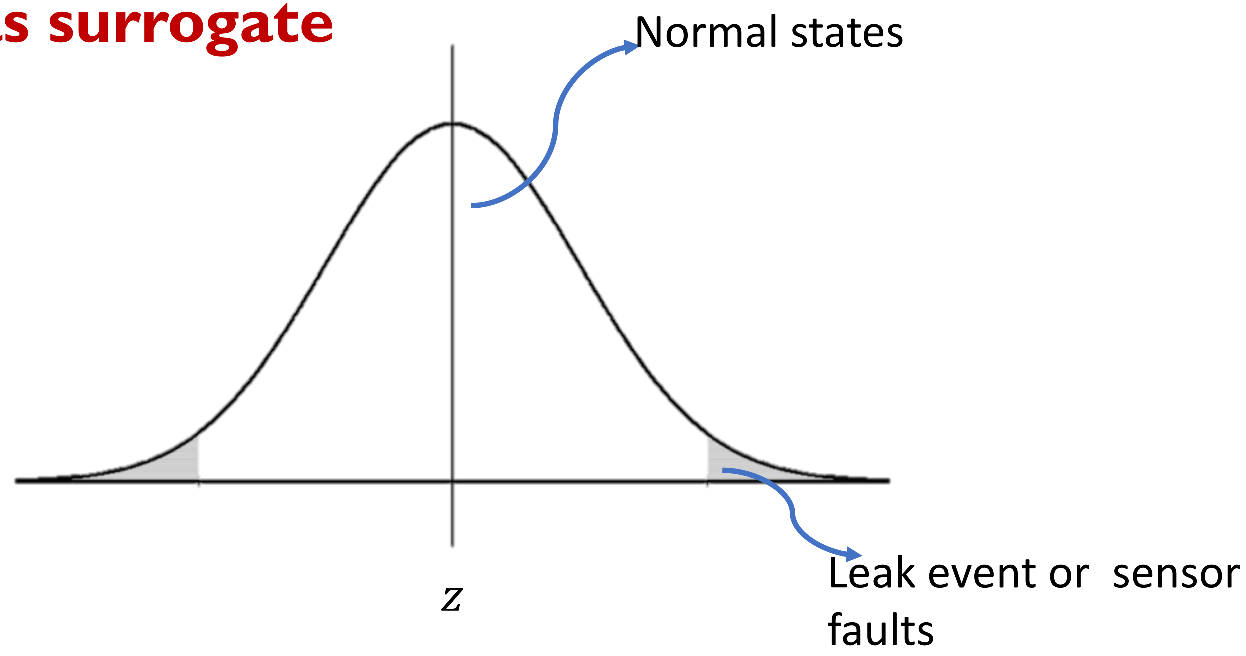
Variational Autoencoders (VAE) as surrogate

- AEs fails to capture the uncertainties in the encoded features in the latent space.
- VAEs aims to capture uncertainties in hydraulic model and stochastic demands for leakage detection and localisation.



Variational Autoencoders (VAE) as surrogate



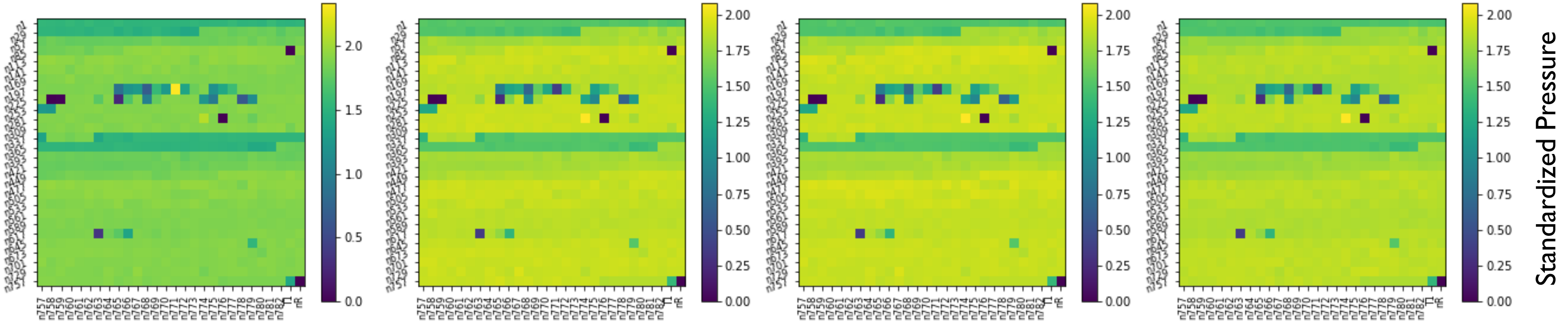


Loss function is sum of reconstruction error and KL divergence measure from prior

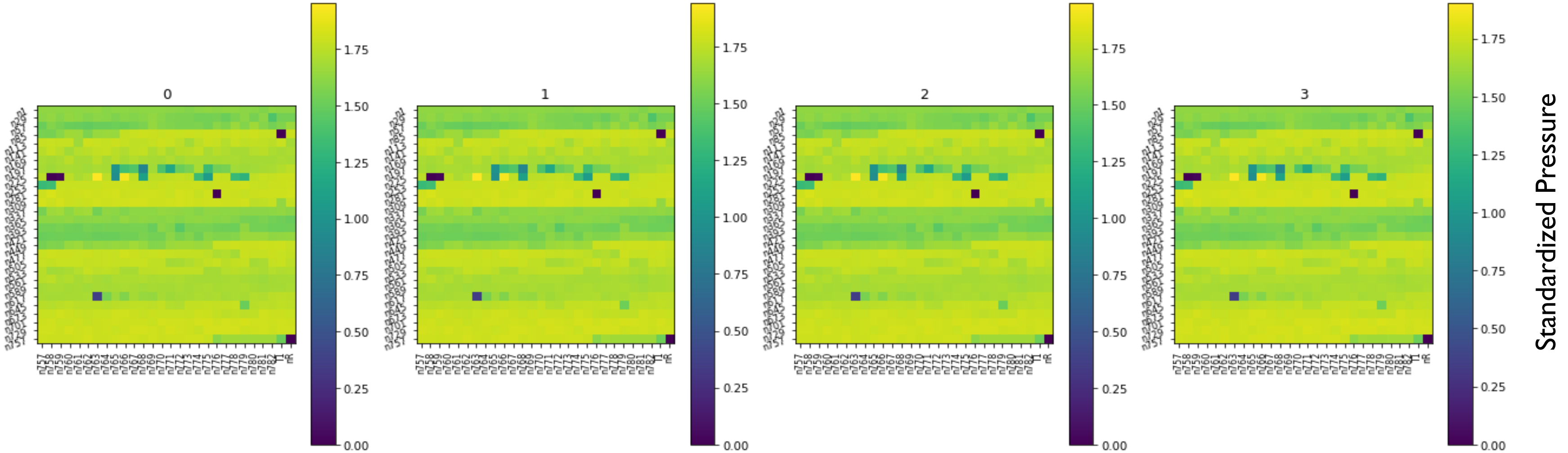
VAE Loss = $\mathcal{L}(x, \hat{x}) + \beta \sum KL\ (q\ (z|x) \parallel p(z))$

Results of VAE as surrogates

Training data



Reconstructed data

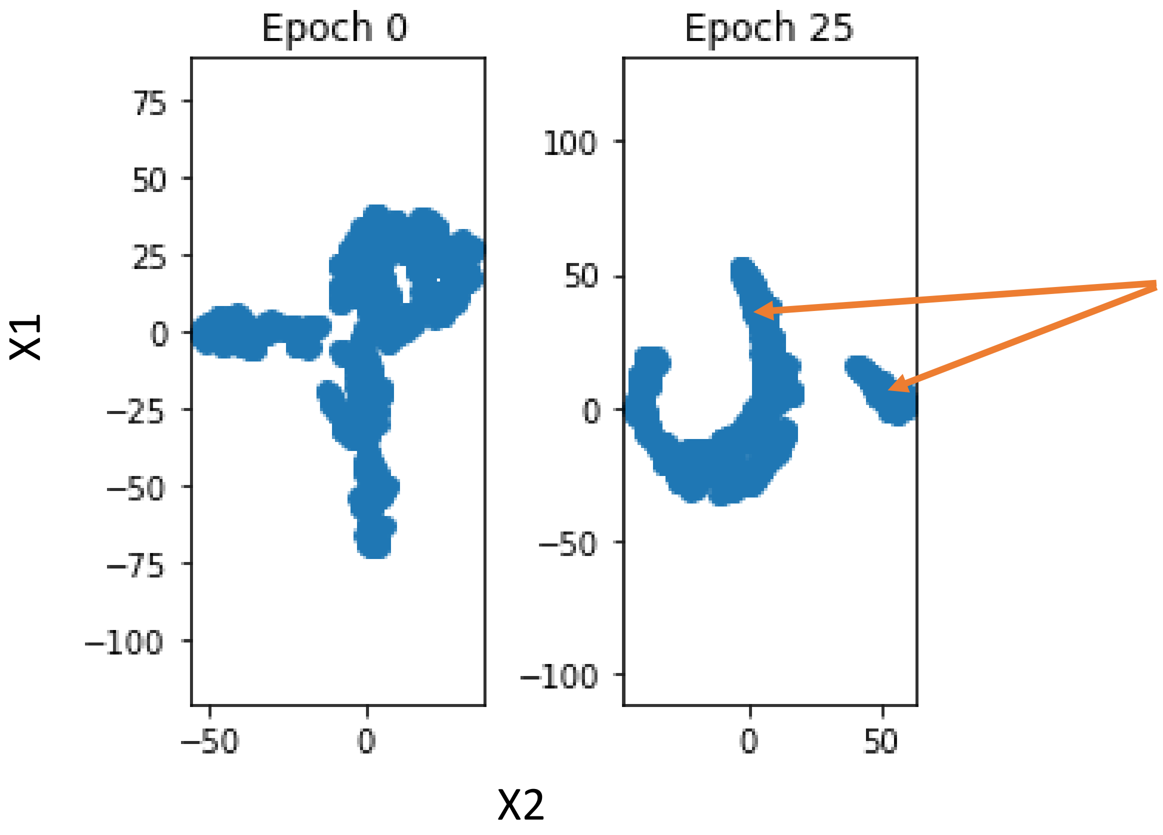


Ideal scenario: Steady states at all nodes are considered

x → 784
z → 20

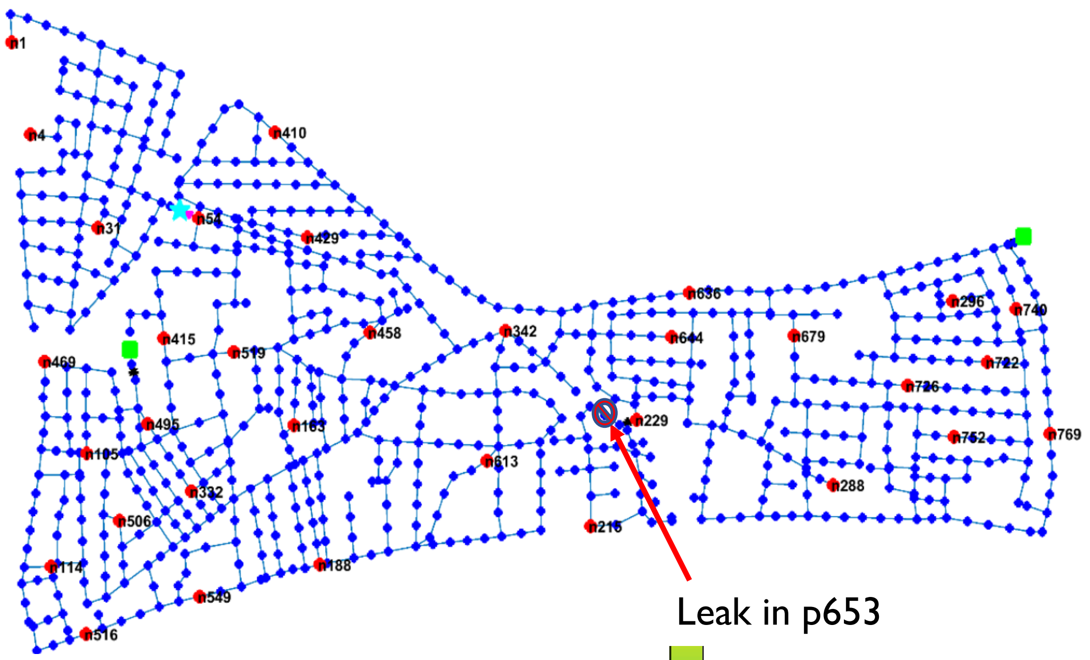
Results of VAE as surrogates

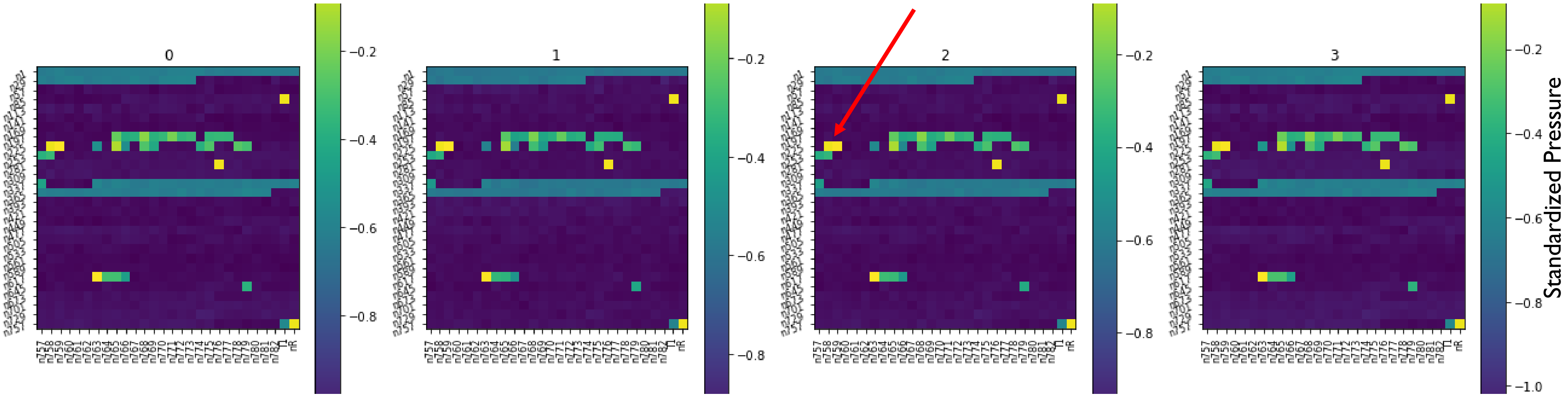
T-SNE Dimensionality Reduction of z



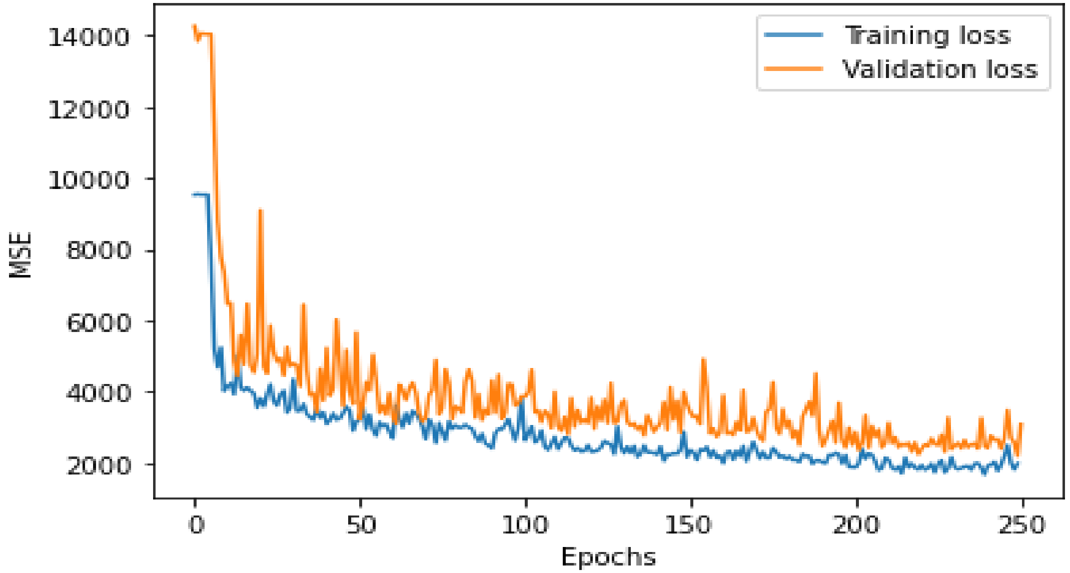
Clear separation between encoded means of z

Results of VAE as surrogates

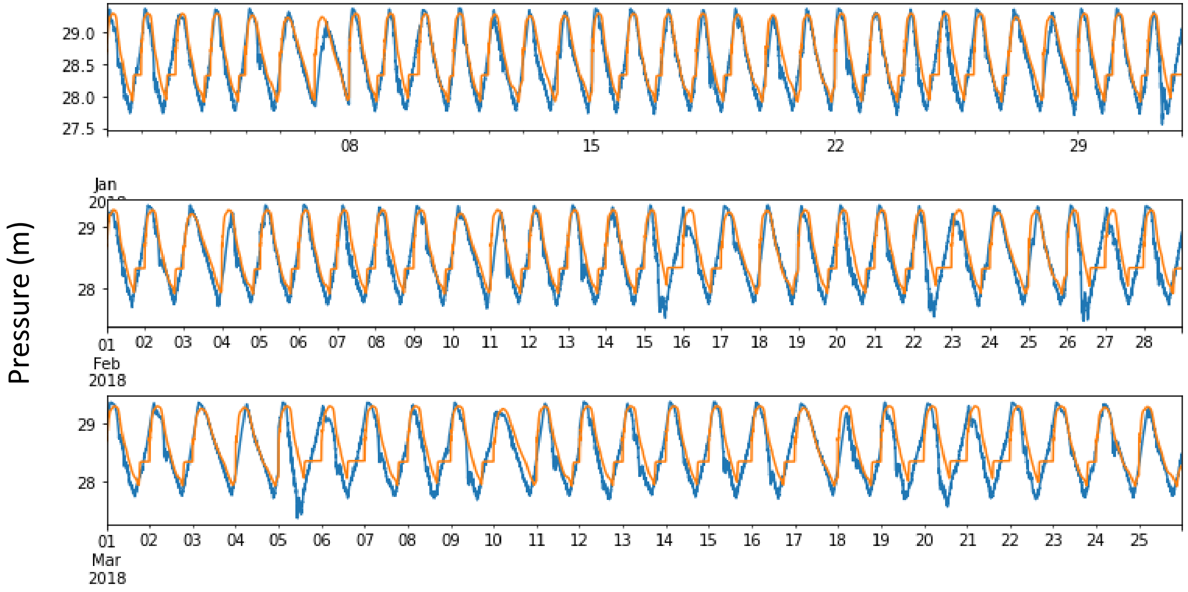




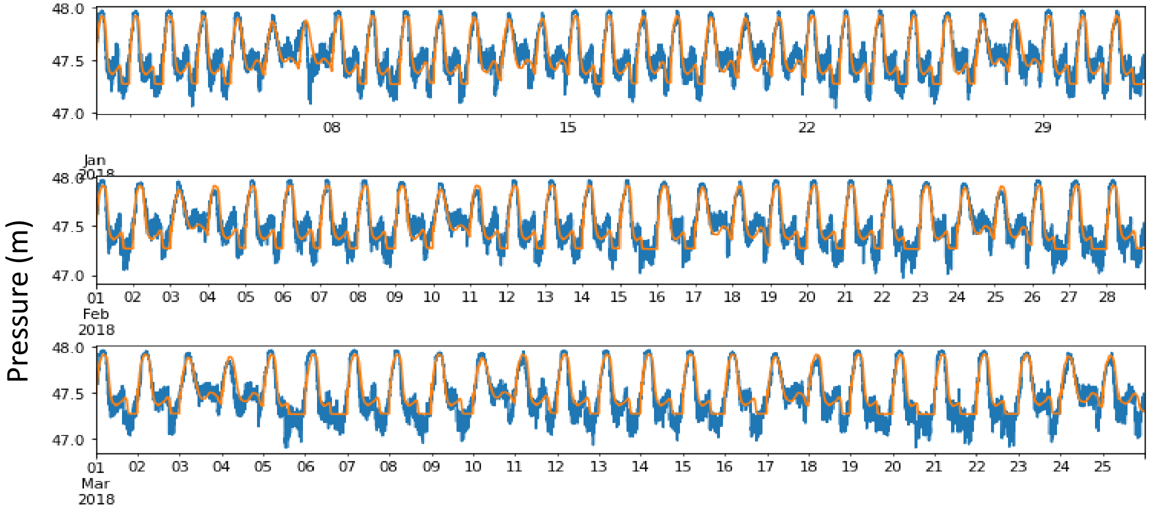
Combining LSTMs with AE



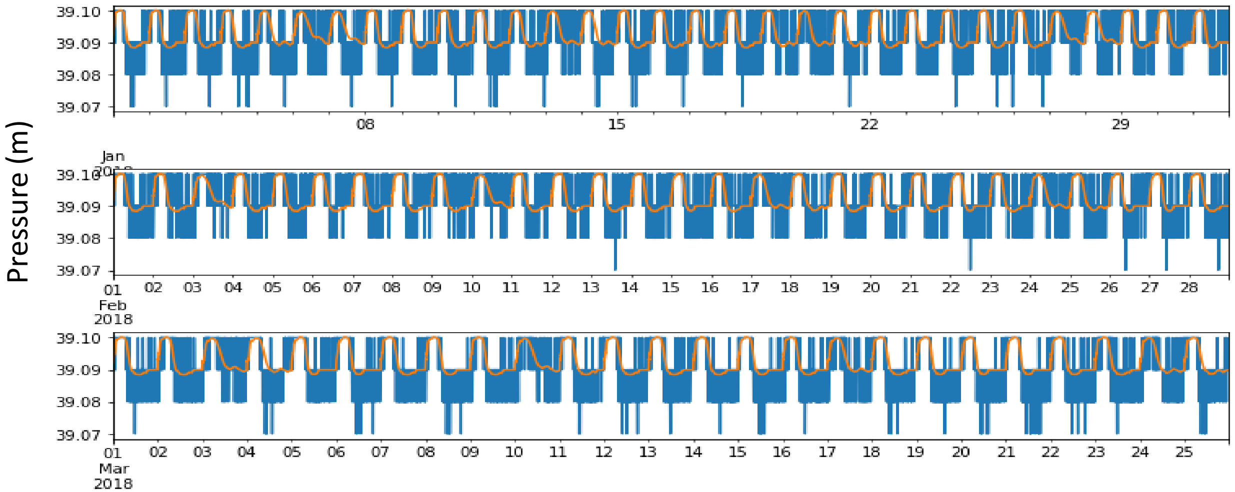
Input/Reconstructions for Sensor n1

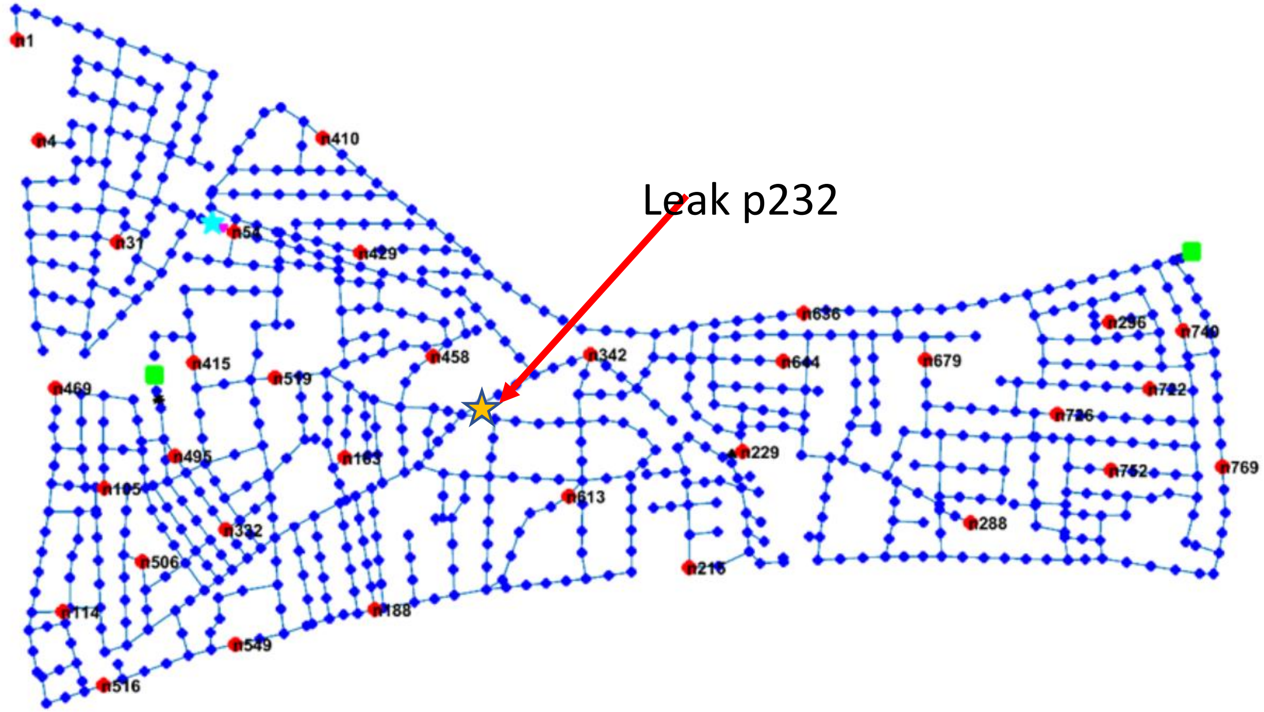


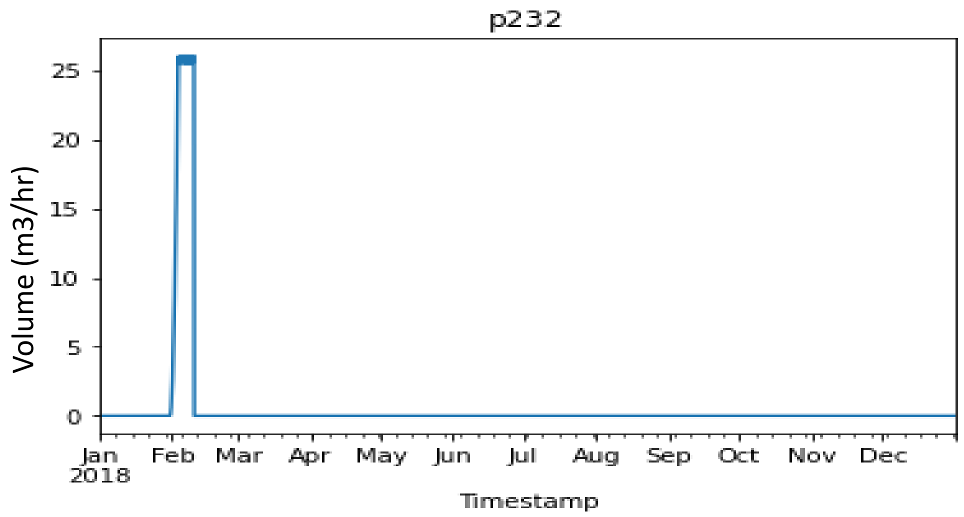
Input/Reconstructions for Sensor n469

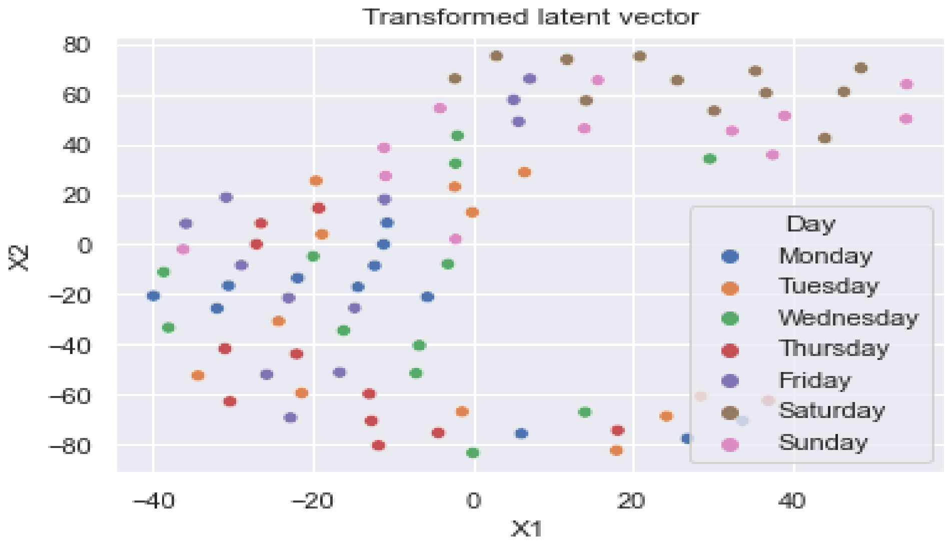


Input/Reconstructions for Sensor n215

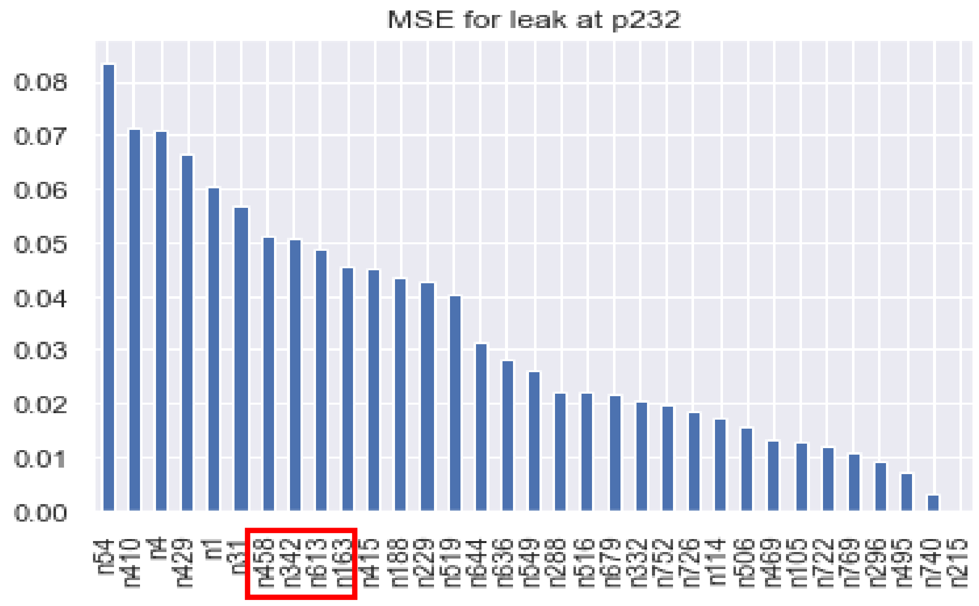




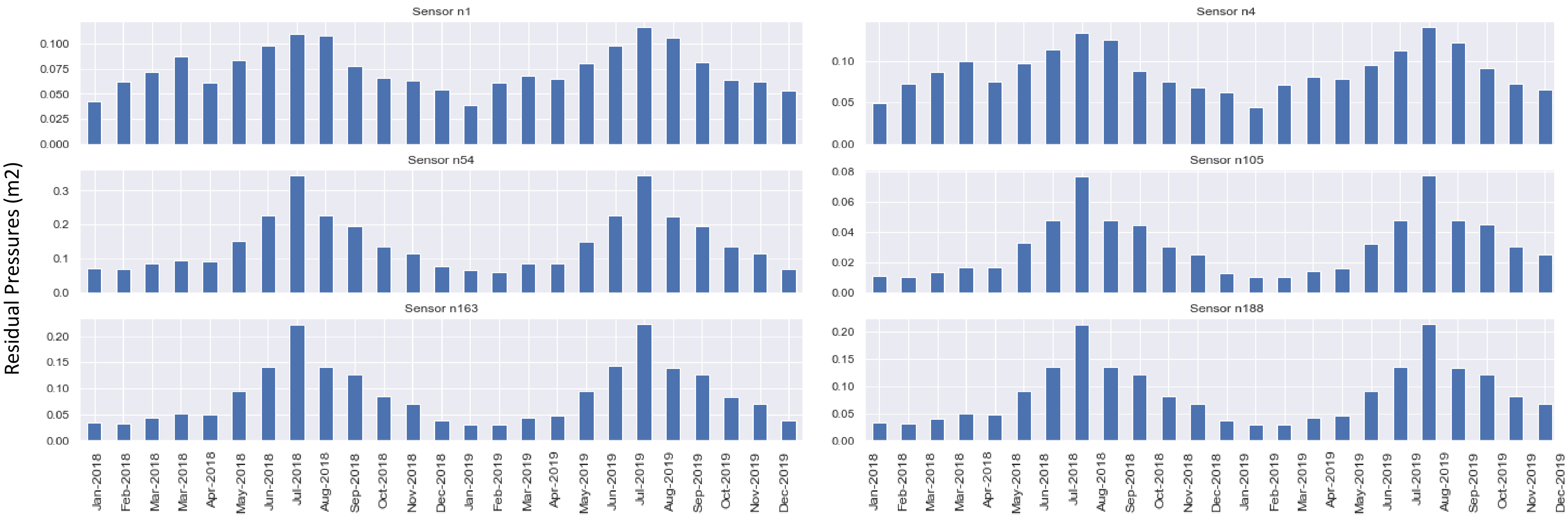




84 calendar days distriubted uniformly



Reconstruction errors and Seasonality



- Residuals reflects long term seasonal behavior

- One possible solution is to include seasonality models and add them with reconstructions

Summary

- Two surrogate models were developed using AE and VAE architectures.
- The methods were tested on artifically simulated dataset from 33 leak events.
- AE performed better at detecting abrupt pipe bursts.
- AE failed at detecting incipient leaks despite the assumption of high number of sensors for the given size of the network.
- Attempts have been made to emulate pressure states at all locations using VAE with gaussian prior and using LSTMs for learning temporal correlations.
- Generative models such as VAE can enrich the information on reconstruction errors and their distributions.

Thank you

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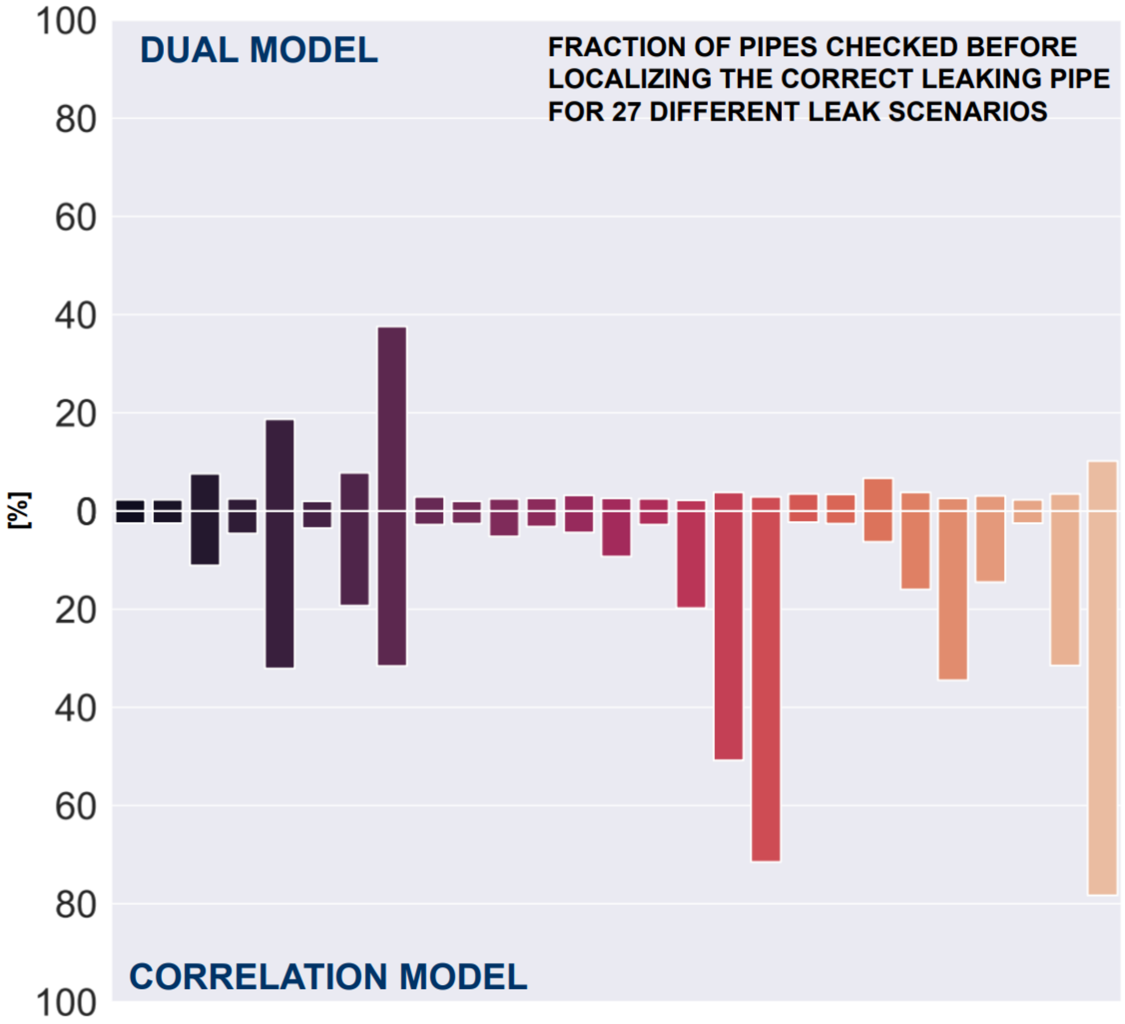
Leak Localization with the Dual Model



Erik Nordahl, Edo Abraham, Jochen Deuerlein, Olivier Piller, Franz Tscheikner-Gratl, David Steffelbauer


DP 53374
www.oslo.kommune.no

Leak status and consequences of leaks

- 32 % in Norway, 23 % in Europe

- Consequences
  - Economy
  - Environment
  - Increased energy use
  - Health

How do we handle leaks today?

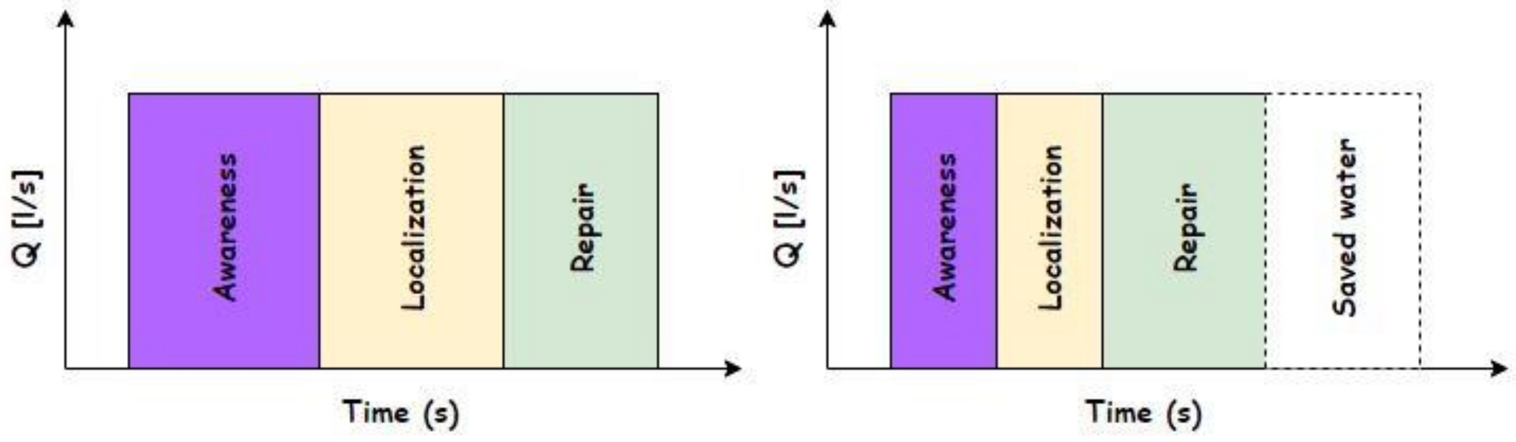
- A passive approach

→ Only reported leaks are fixed

→ Leads to large volumes of lost water

How should we handle leaks?

- **The active approach** aims to limit the impact of leaks
  - Network monitoring
  - Network examining
  - Or other tools which are:
    - Proactive
    - Predictive



But…

The currently most commonly used methods have some limitations:

- Ineffective
- Expensive
- Inconsistent performance
- Labor-intensive

Model-based leak localization

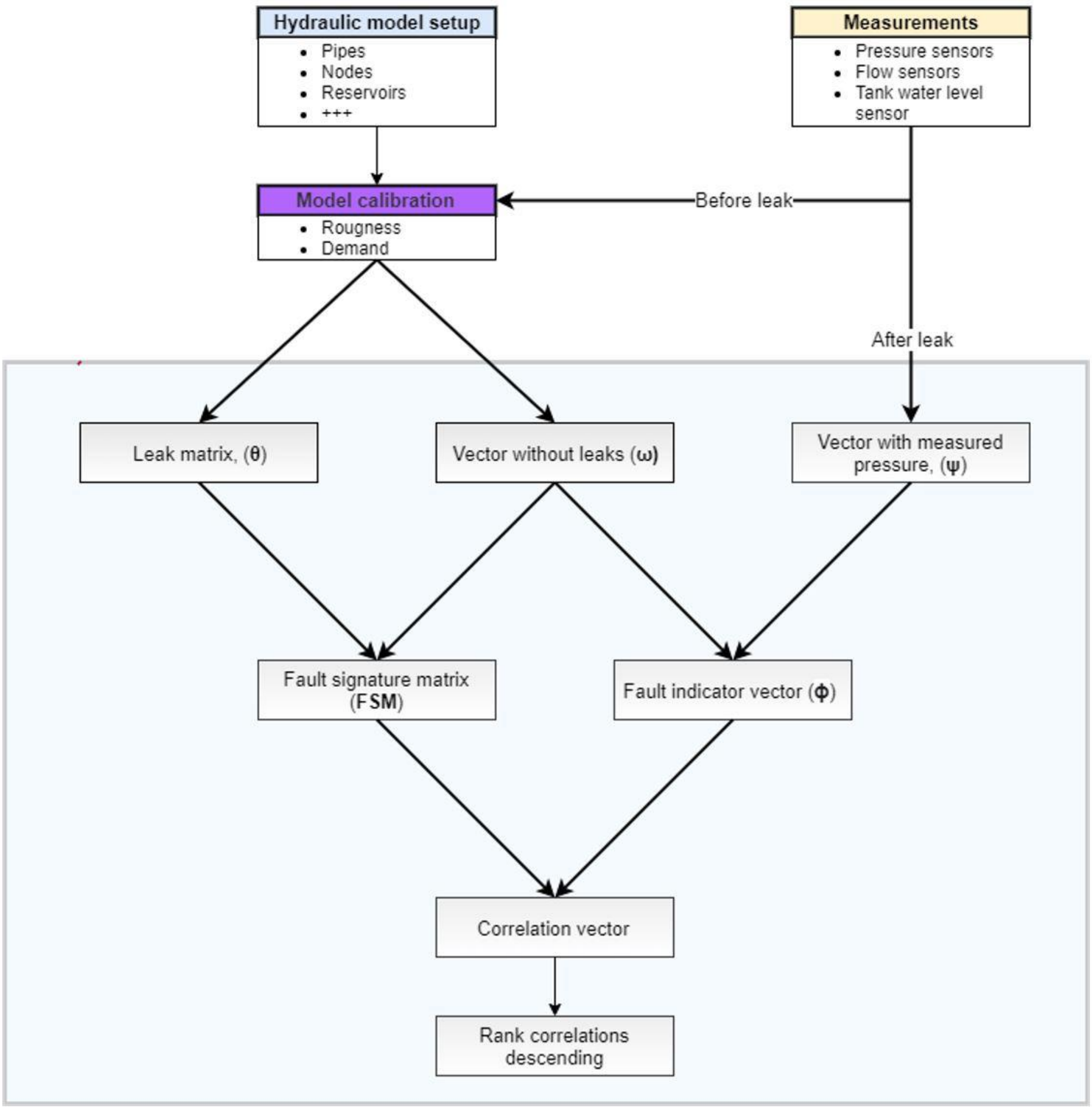
- Tries to circumvent these shortcomings in finding leaks by:
  - Comparing estimates from hydraulic simulations
  - With real data

  - Advantageous because:
    - Cost-efficient
    - Utilizes sensor technology
    - Performs well regardless of pipe material

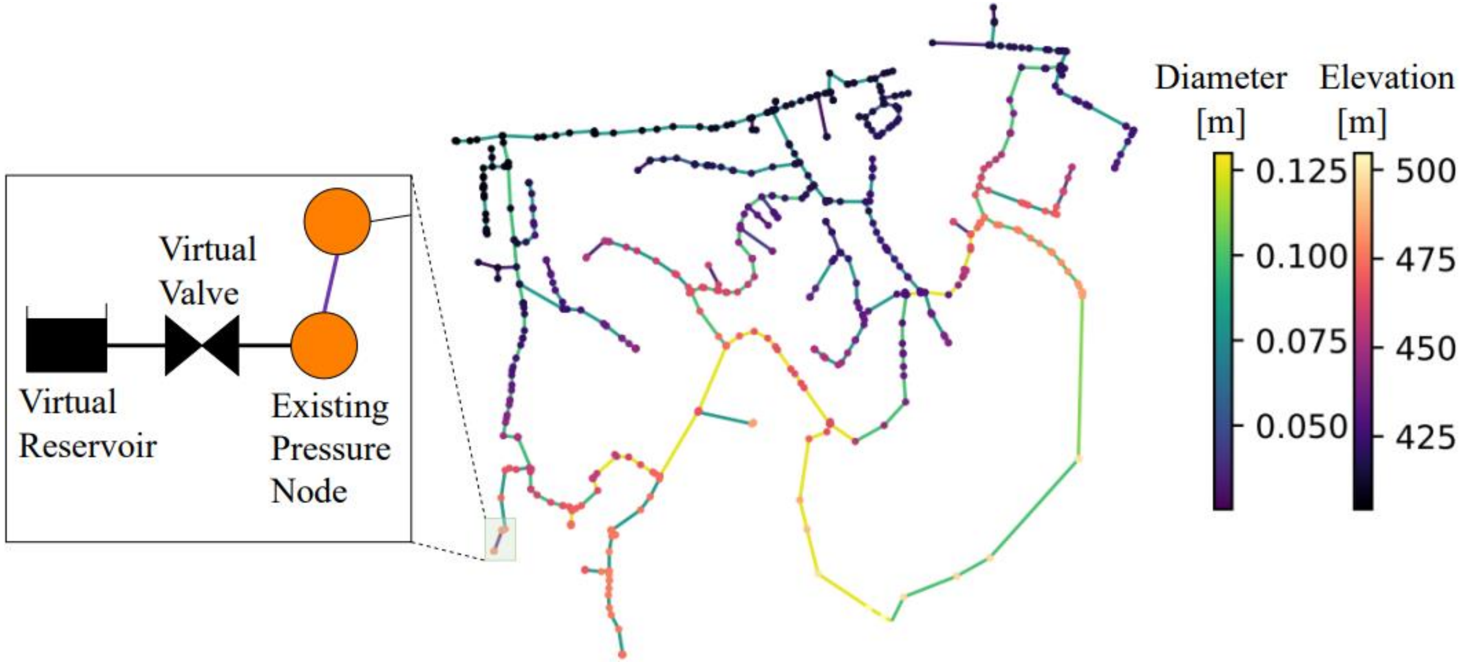
Model-based leak localization - challenges

- Currently used on:
  - Virtual networks
  - Small uncomplicated real networks
  - Very large leak scenarios
  - → **Model-based leak localization is rarely seen outside of the academic environment**

Correlation Model



Dual Model



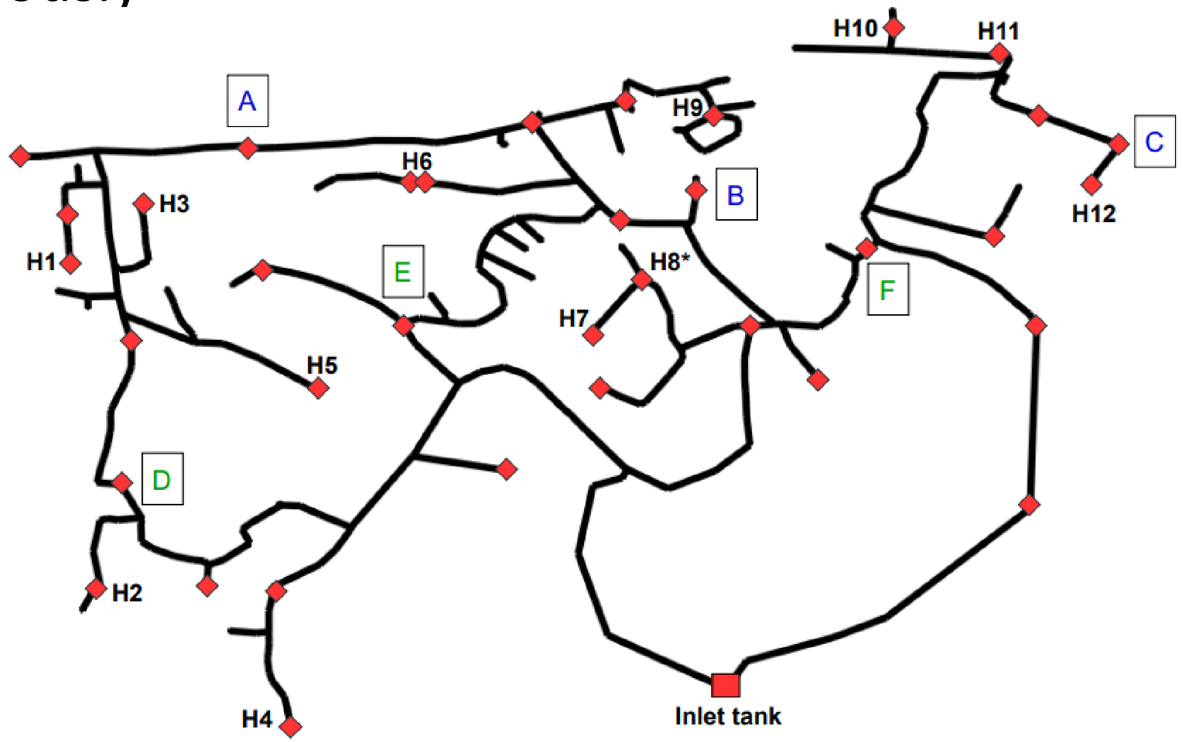
Virtual
Valve
Virtual
Reservoir
Existing
Pressure
Node
Diameter
[m]
Elevation
[m]
0.125
0.100
0.075
0.050
500
475
450
425

Aim of the paper

- Test the Dual Model in a real-world case-study
- Compare it with the Correlation Method
- Test for different:
  - Leak types
  - Leak locations
  - Model calibrations
  - Number of sensors

Case-study: Graz-Ragnitz, Austria

- Open hydrants to simulate leak scenarios
  - 17 leaks
  - Single and multiple leaks simultaneously
- Measure
  - Pressure – 12 sensors
  - System inflow
  - Leak size



Hydraulic model calibration

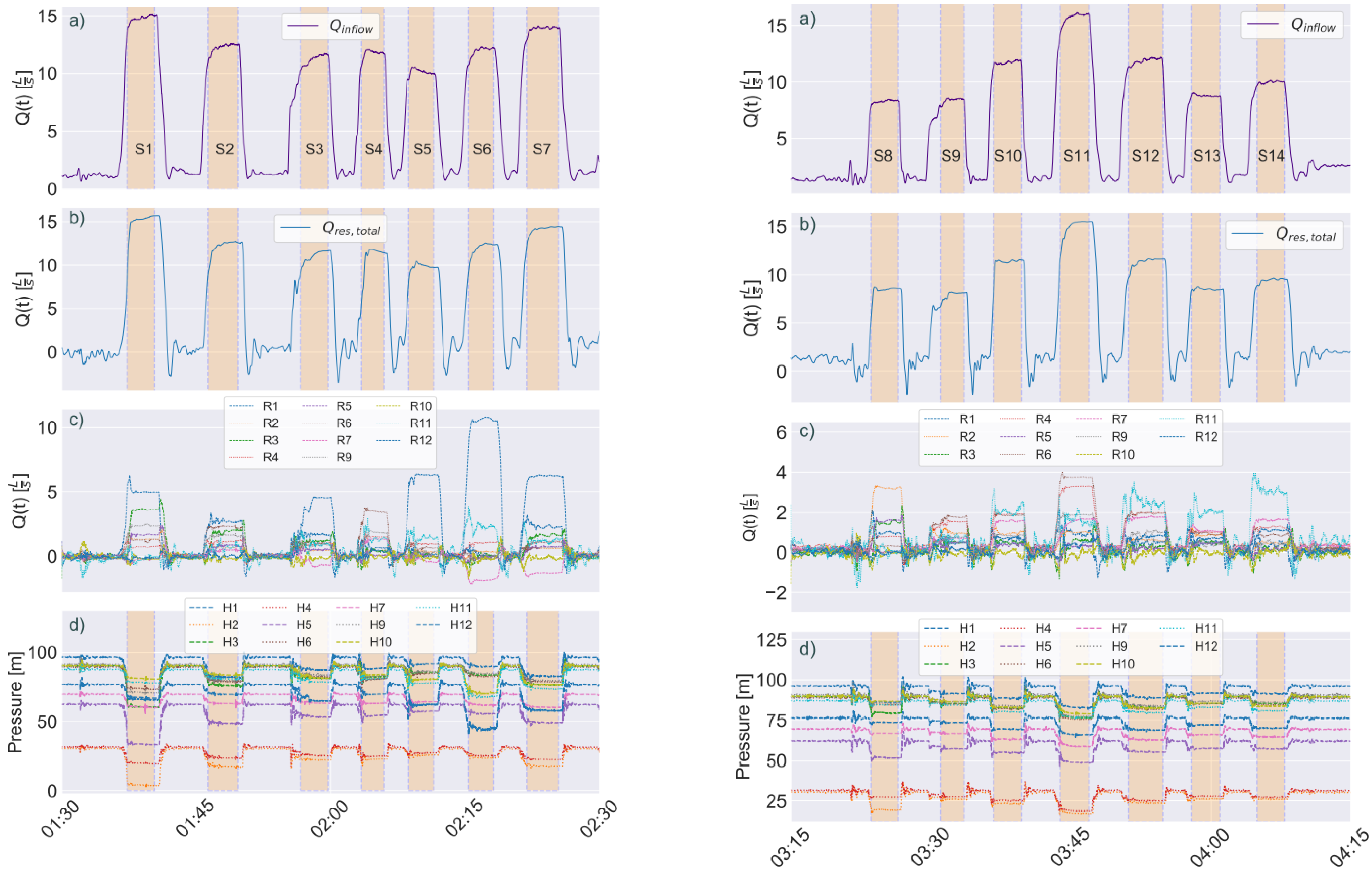
- Three different calibrations created
- C1: only calibrated for demand
- C2: calibrated for elevations + C1
- C3: roughness and minor loss + C2

Adjustments on measurements

- Tank level
  - Approximated with second-order splines
- Pressure sensors
  - Resampled to produce one value every minute
- Sensor clocks
  - Corrected manually

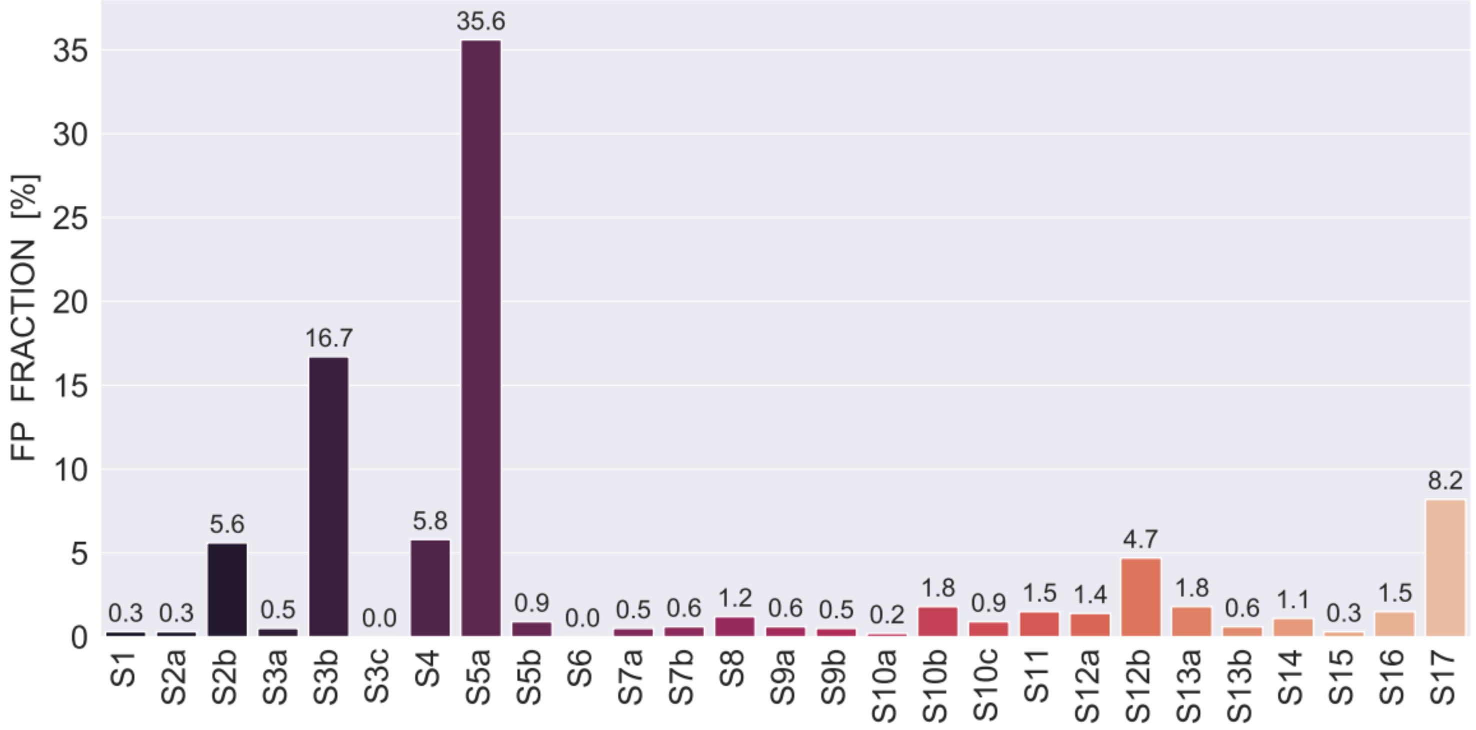
Evaluation criterias

- Topological Distance [m]
  - Distance from suggested leak location to real leak location
- False Positive Fraction [%]
  - Fraction of pipes suggested before the correct pipe
- Maximum Span [m]
  - Max distance between two FP-pipes



a)
Q_{inflow}
Q(t) [L/s]
S1
S2
S3
S4
S5
S6
S7
b)
$Q_{res,total}$
c)
R1
R2
R3
R4
R5
R6
R7
R9
R10
R11
R12
d)
H1
H2
H3
H4
H5
H6
H7
H9
H10
H11
H12
Pressure [m]
01:30
01:45
02:00
02:15
02:30
S8
S9
S10
S11
S12
S13
S14
03:15
03:30
03:45
04:00
04:15

Dual Model results with best-calibrated model

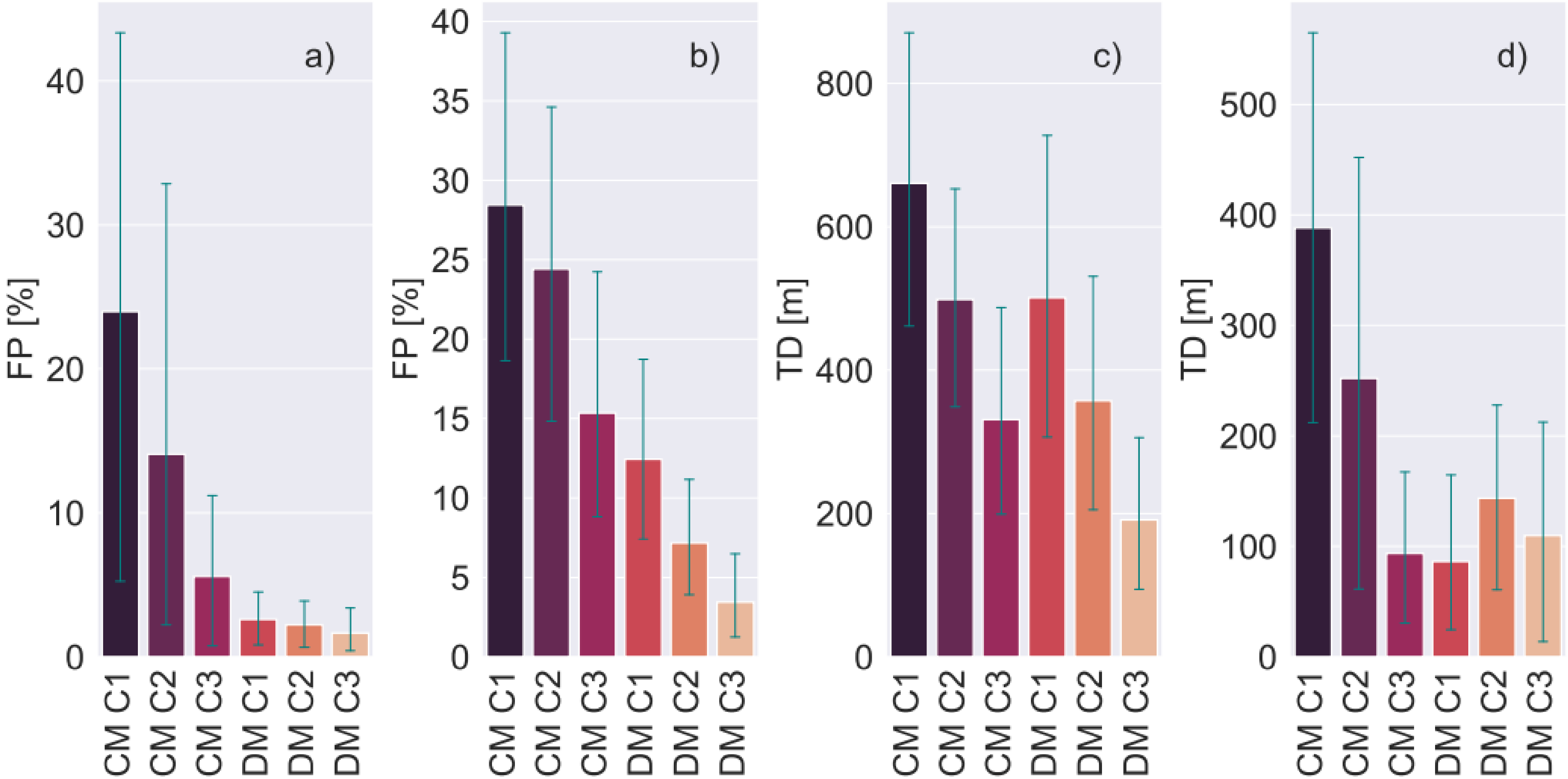


- <u>Dual Model</u>
- 21 out of 27 leaks: FP < 2 %
- Can localize small leaks

- <u>Correlation Method</u>
- 9 out of 27 leaks: FP < 2 %
- Unable to localize leaks smaller than 3 L/s

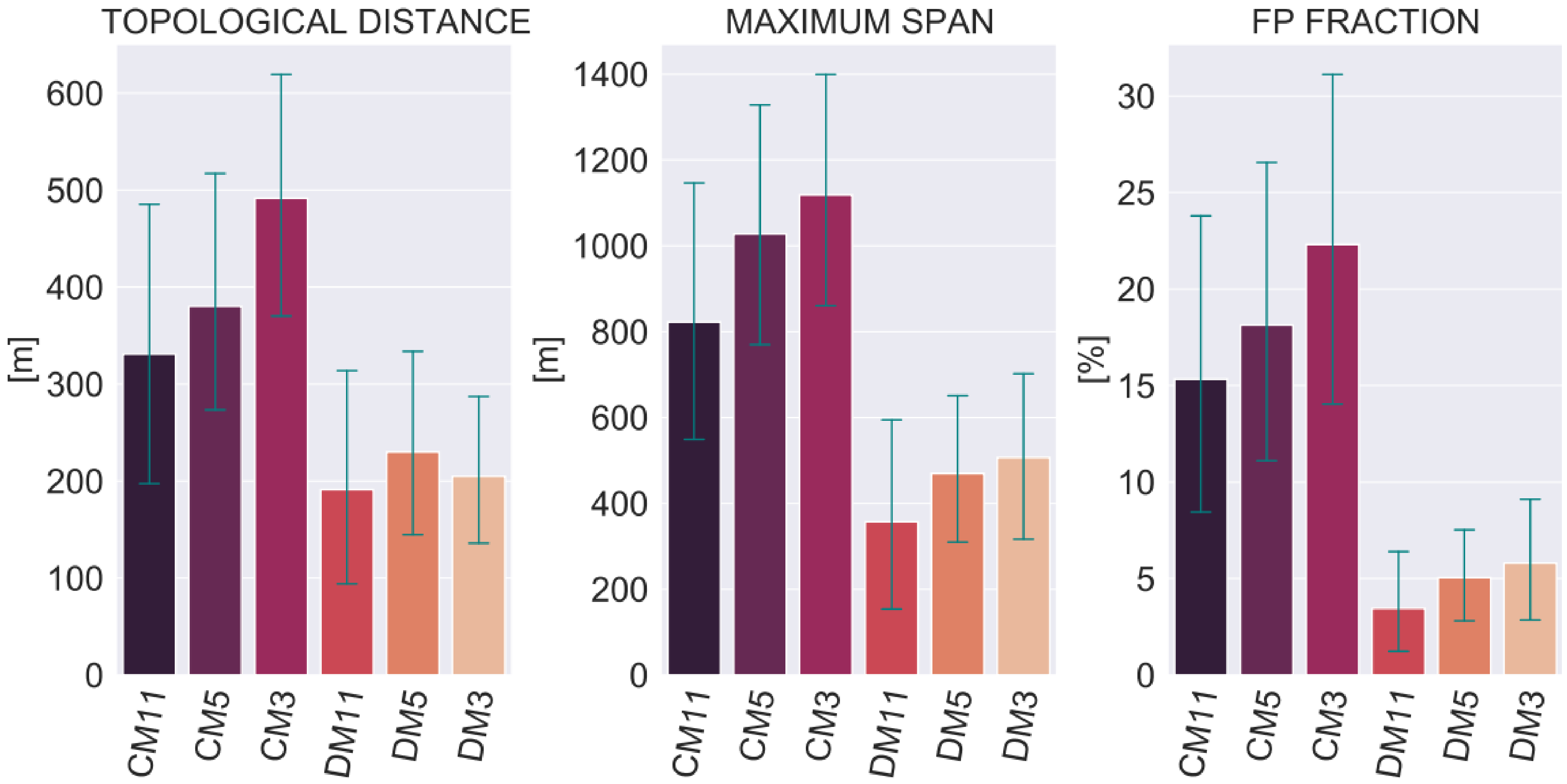
- **Dual Model outperforms!**

Results with different calibrations

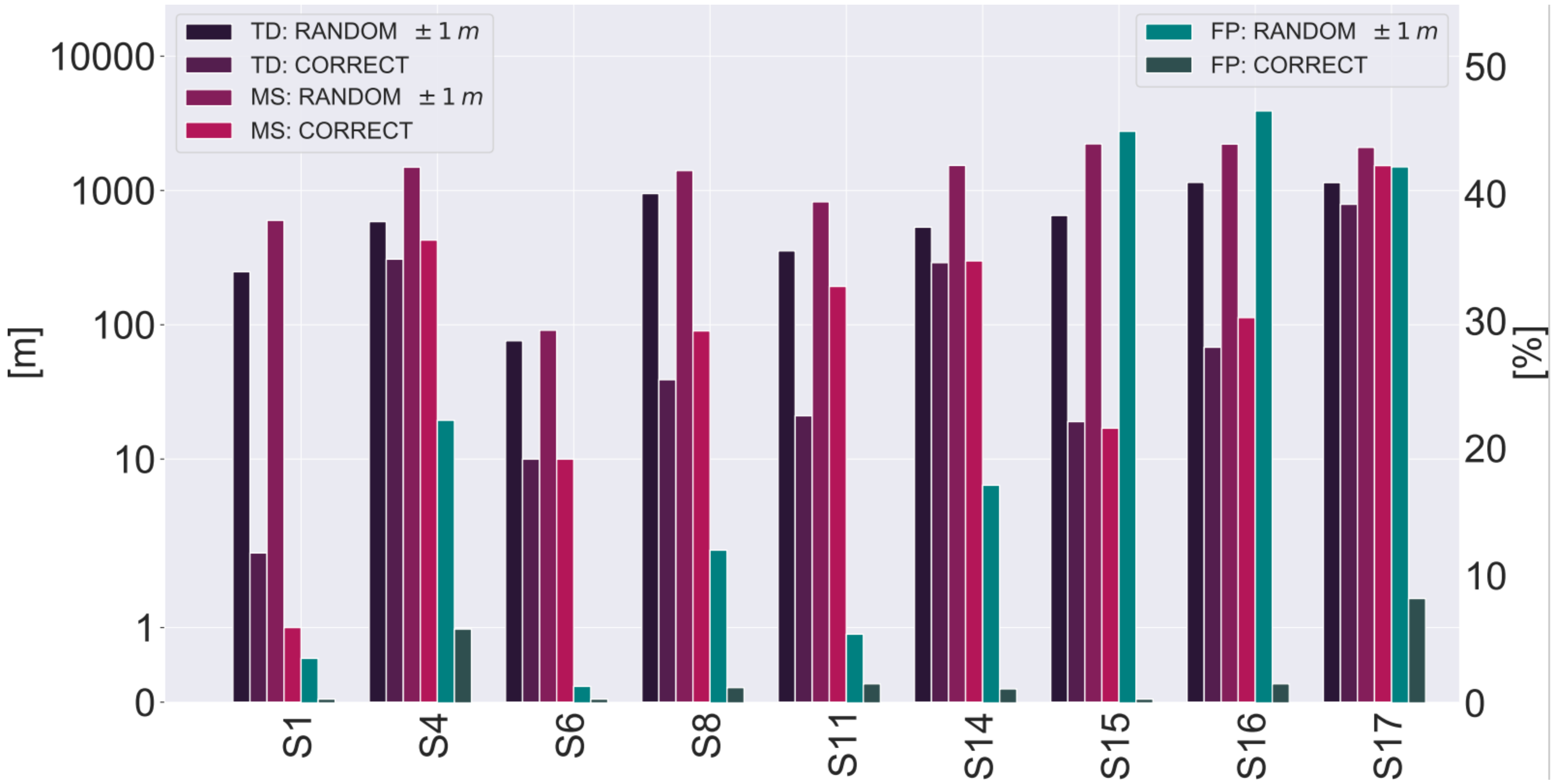


Large leaks | All leaks | Large leaks | All leaks

Results with different number of sensors



Limitations of the Dual Model



Possibilities with the Dual Model

- Handle uncertain input
- Functions well with several leaks present
- Robust

Conclusion

- The Dual Model **can localise real leaks** with different locations and magnitudes

(1 L/s to 15 L/s)

- The Dual Model can localise leaks **without a well-calibrated model**, which is a significant advantage for water utilities.

- The Dual Model shows better performance with three pressure sensors than the more commonly used Correlation Method obtained with 11 pressure sensors

- The Dual Model's main limitations are that the model is sensitive to the leak's location in the water distribution network and that the nodal elevations must be adjusted

Thank you for your attention!

- Contact information:

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green 2050

GRAPH NEURAL NETWORKS FOR WATER DISTRIBUTION SYSTEM MODELLING

Bulat Kerimov (NTNU), Riccardo Taormina (TU Delft), and Franz Tscheikner-Gratl (NTNU)

Hydraulic models

Hydraulic simulators are widely used
But can computationally expensive for applications like

- Design and optimization
- Criticality assessment
- Real-time control
- Core model of a digital twin

Surrogate models

Artificial Neural Networks (ANNs) are well established candidates for a surrogate model

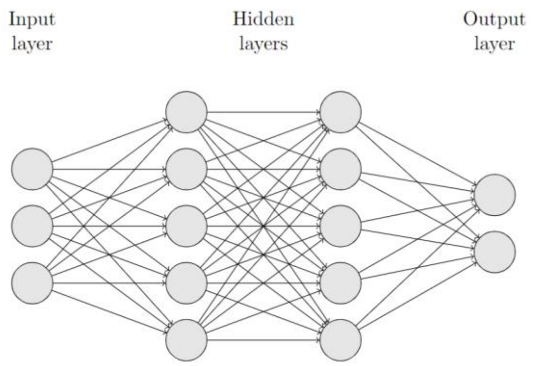


Figure 1 - Schematic artificial neural network

However, they need to be retrained for every change in the topology

Graphs in WDS

Graph is a mathematical representation of a network

- $G=(V,E)$

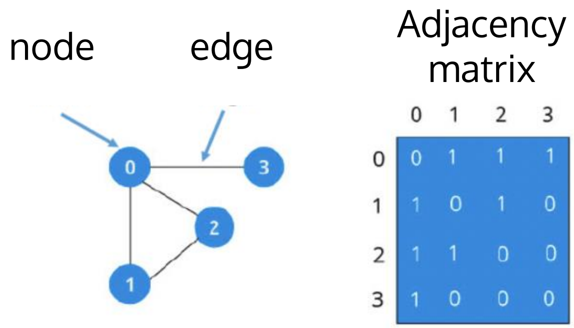


Figure 2.A - example of a graph

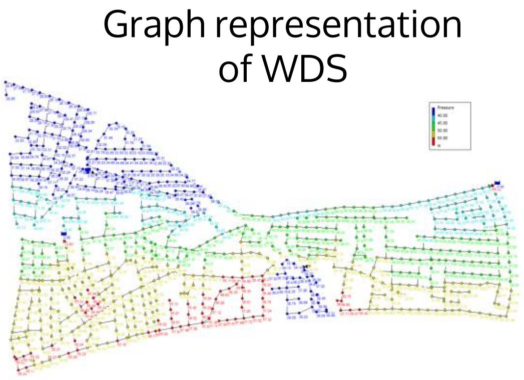


Figure 2.B - network layout of L-Town water system

GNNs as surrogate models

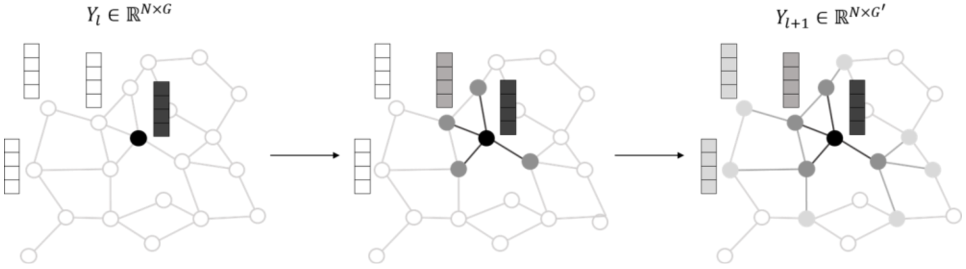


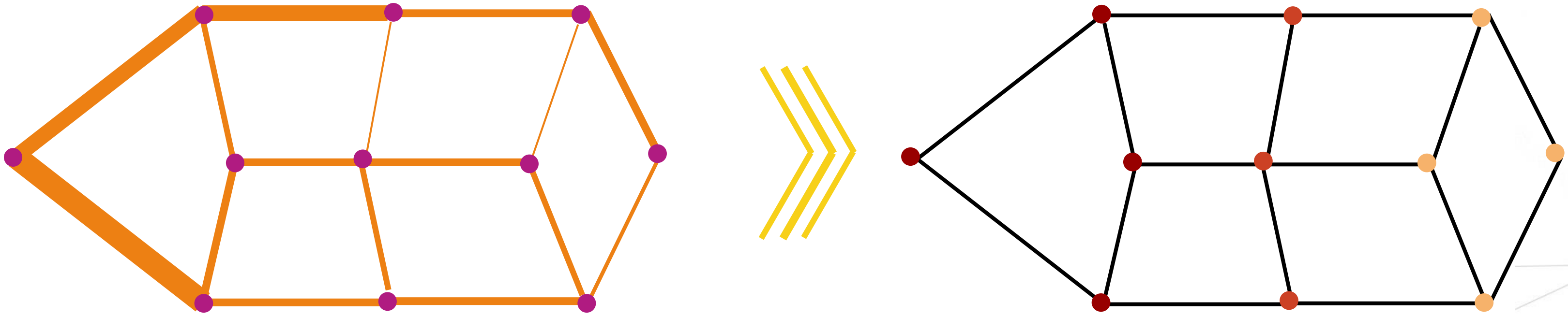
Figure 3. A graph neural network (GNN) layer with a 2-hop neighbourhood. The figures from left to right indicate how the node signal in the black node propagates throughout the network. The same reasoning is applied for every other node in the graph.

However, there is no evidence of good transferability properties

Edge-level representation

Step 2: Pressure estimation

Second step is based on Hazen-Williams equation and a matrix inversion



Step 1:
Flowrate interpolation

Step 2:
Headloss reconstruction

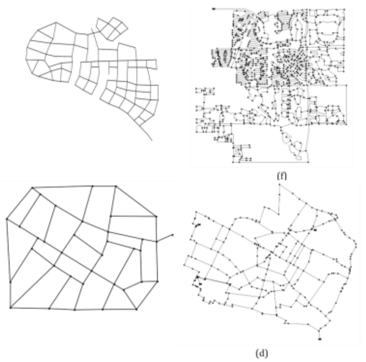
Experiments

Compare accuracy of the model with the state of the art

i. On the same network topology (In-the-domain)
ii. On the unseen before network (Out-of-domain)

Dataset generation

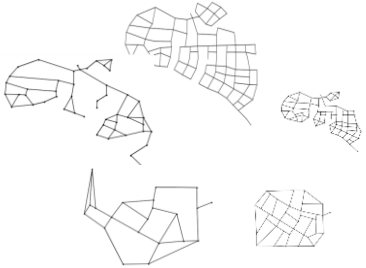
8 base water networks from the literature



Introduced variability

- Varying demands
- Variable pipe parameters
- Varying topology

~60 000 generated simulation



Results: In the domain performance

Dataset with varying demands, $R^2 = \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2}$

		Water network						
	Model	L-Town	Net-3	Pescaria	KL	MOD	Asnet2	ZJ
heads	GNN	0.996	**0.993**	**0.999**	0.693	**0.998**	**0.986**	**0.997**
	Ours	**0.998**	0.956	0.968	**0.902**	0.970	0.983	**0.997**
flowrates	GNN	0.989	0.001	0.246	0.663	0.182	0.907	0.956
	Ours	**1.000**	**0.991**	**0.994**	**0.896**	**0.998**	**0.994**	**1.000**

Table 1: Comparison of performances of surrogate models **pressures** and **flowrates**

Results: Out-of-domain performance

Model tested on 2 networks that were not present in the dataset

$$R^2 = \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2}$$

Water flowrates

Model	Asnet2	ZJ
Ours	0.983	0.862

Table 2: Evaluation of transferability on unseen networks

Conclusion

- We proposed a candidate for a surrogate model of WDS
- Such model accurately reproduces flowrates
- Edge-centric GNNs show higher potential for transferability than a traditional GNN

Thank you!

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Evaluating the generalizability and transferability of water distribution deterioration models

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Purpose and Objectives

The problem

- Small municipalities not benefiting from machine learning (ML) trained models

Objectives

- Evaluate if a “Global” model which is trained with many municipalities’ pipe break data can be useful for the prediction of another municipality’s pipe breaks
- Similarly, evaluate the transferability of a “local” model

Data

- Predictions based on historical break data

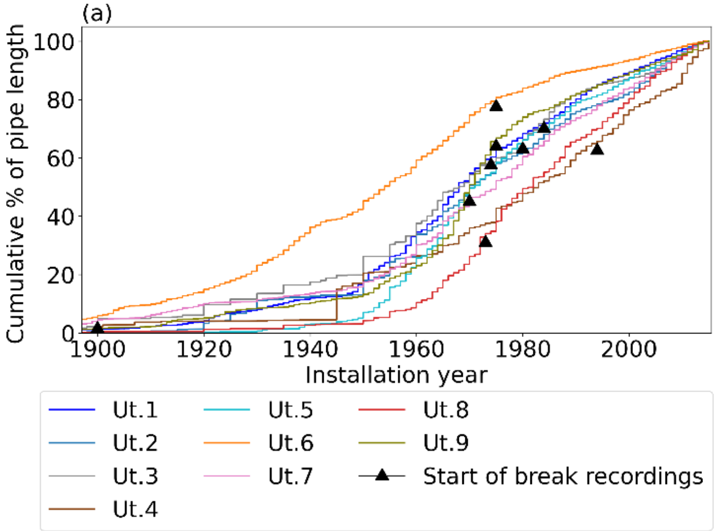
Data:

- Water distribution network of 9 municipalities of Norway
- Total length of pipes =

~ 7000 km

Break records started around **1970s**
Left-truncated data: breaks happened before 1970

The first break of pipe matters a lot!

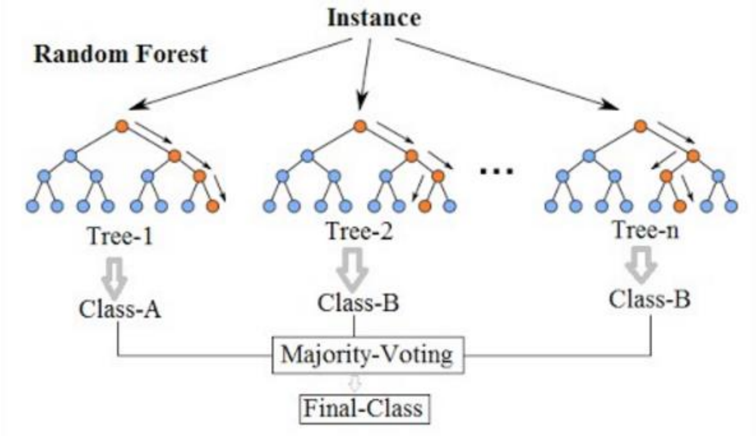


In order to capture the first break records, all pipe installed **before 1945** are discarded (19% of the data)

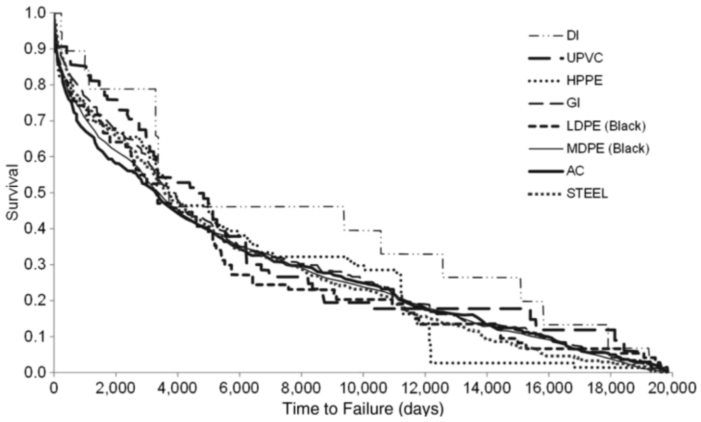
Still not know is the **reason** of the breaks!

Method: Random Survival Forest (RSF)

Random Forest



Survival modeling



Random Survival Forest (RSF): A combination of Random Forest and survival models

Ishwaran, H., Kogalur, U. B., Blackstone, E. H., & Lauer, M. S. (2008). Random survival forests. *The annals of applied statistics*, *2*(3), 841-860

Random Survival Forest - Performance evaluation

Concordance index (C-index) is the metric to evalute the performance of RSF

Observed	Predicted probability of failure
1 (failed)	0,91
1 (failed)	0,72
1 (failed)	0,60

Observed	Predicted probability of failure
0 (not failed)	0,75
0 (not failed)	0,62
0 (not failed)	0,60

C-index = (5+0,5)/9

= 0,61

C-index:
0,5 – random model
1,0 – perfect model
0,0 – perfectly wrong model

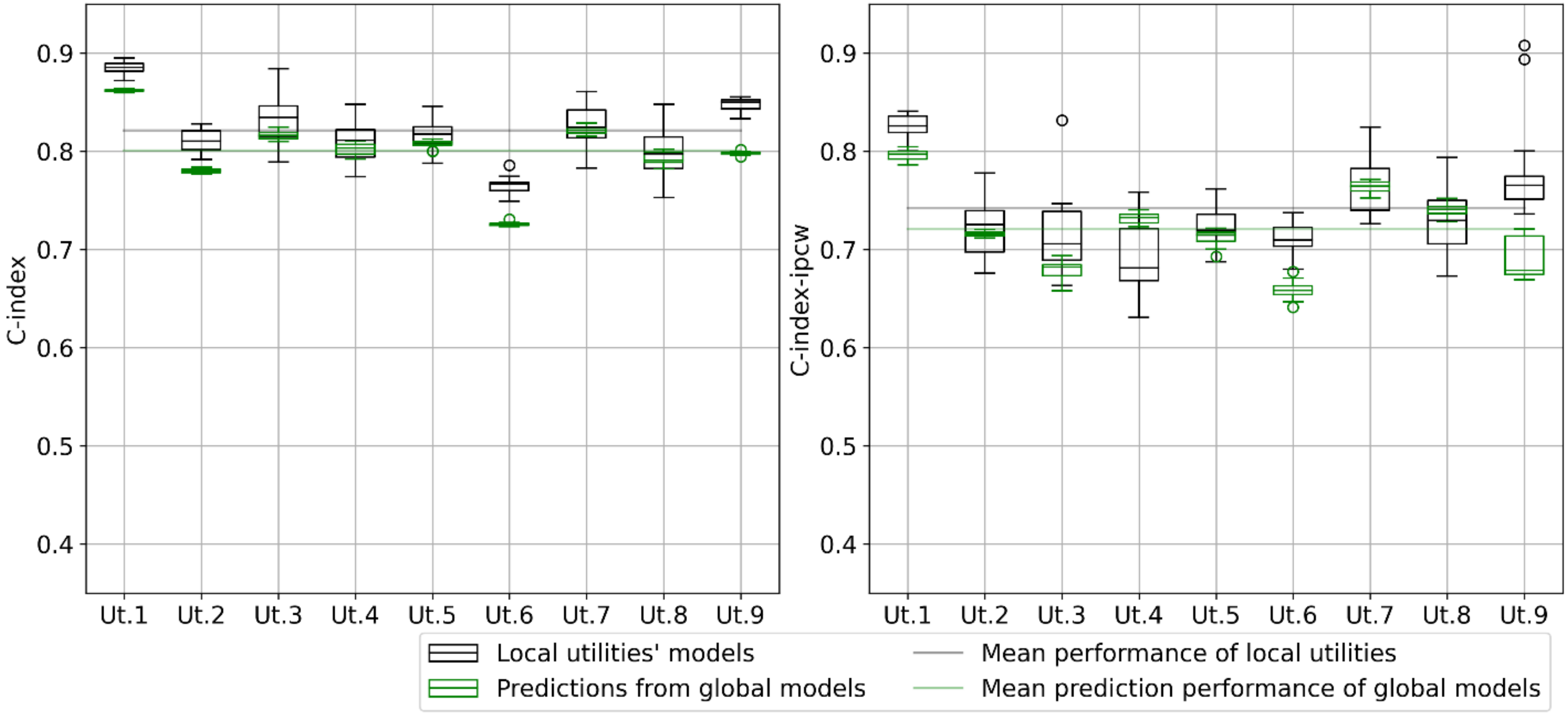
	Concordants (1 point)	Discordants (0 point)	Tied (0.5)
1	0,91 - 0,75	0,72 – 0,75	0,60 – 0,60
2	0,91 – 0,62	0,60 – 0,75	
3	0,91 – 0,60	0,60 – 0,62	
4	0,72 – 0,62		
5	0,72 – 0,60		

C-index-ipcw

For high amount of censored data: C-index overestimates performance, use instead **C-index-ipcw**

Results

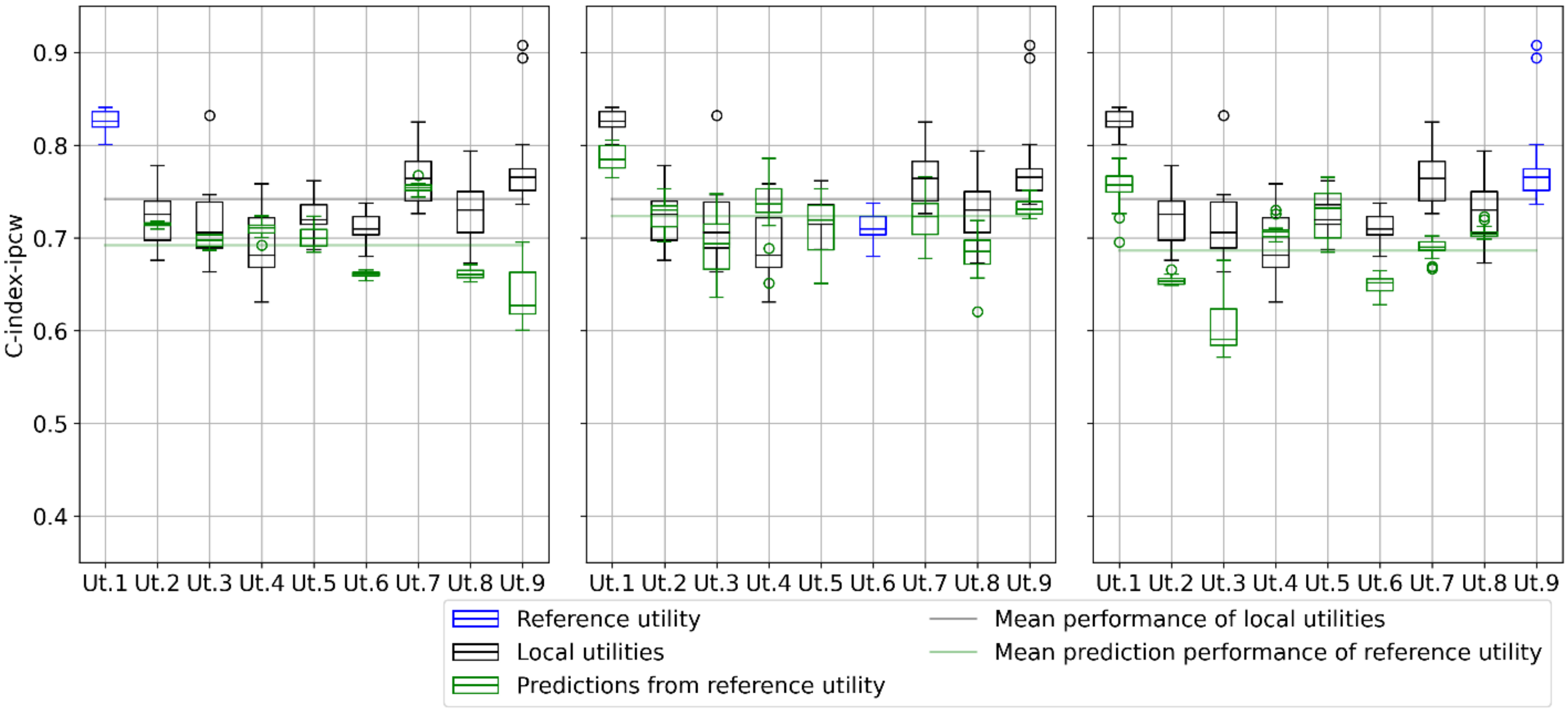
Prediction performance of global models



NTNU

Results

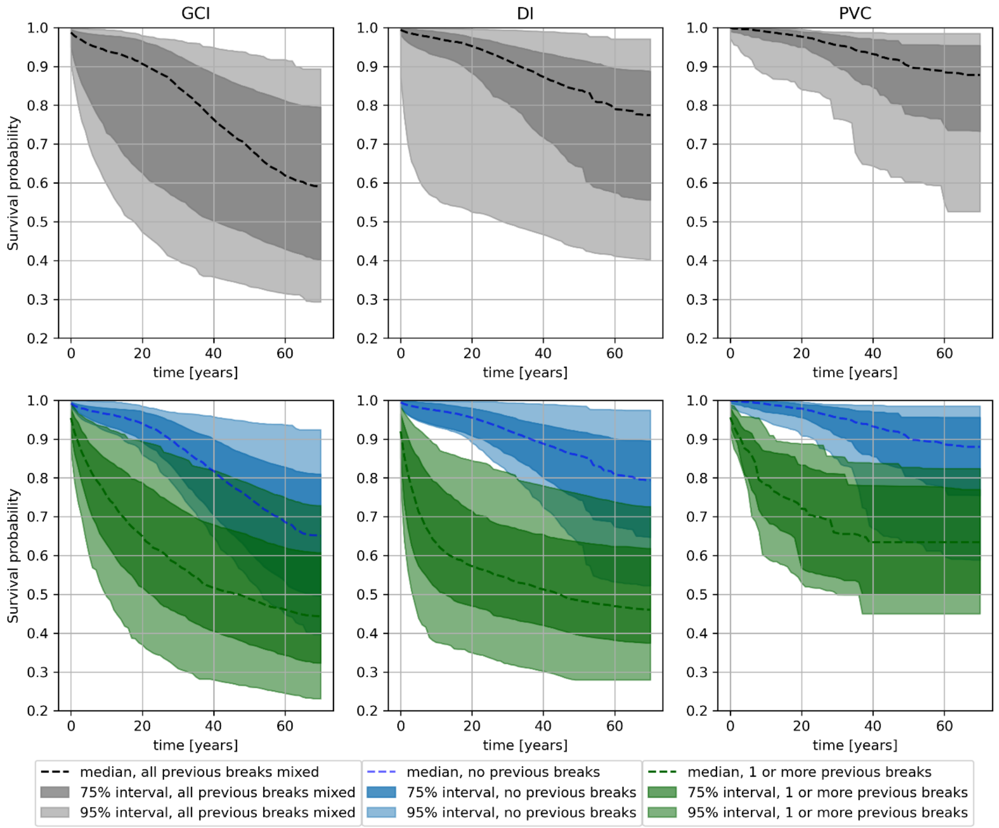
Prediction performance of reference models



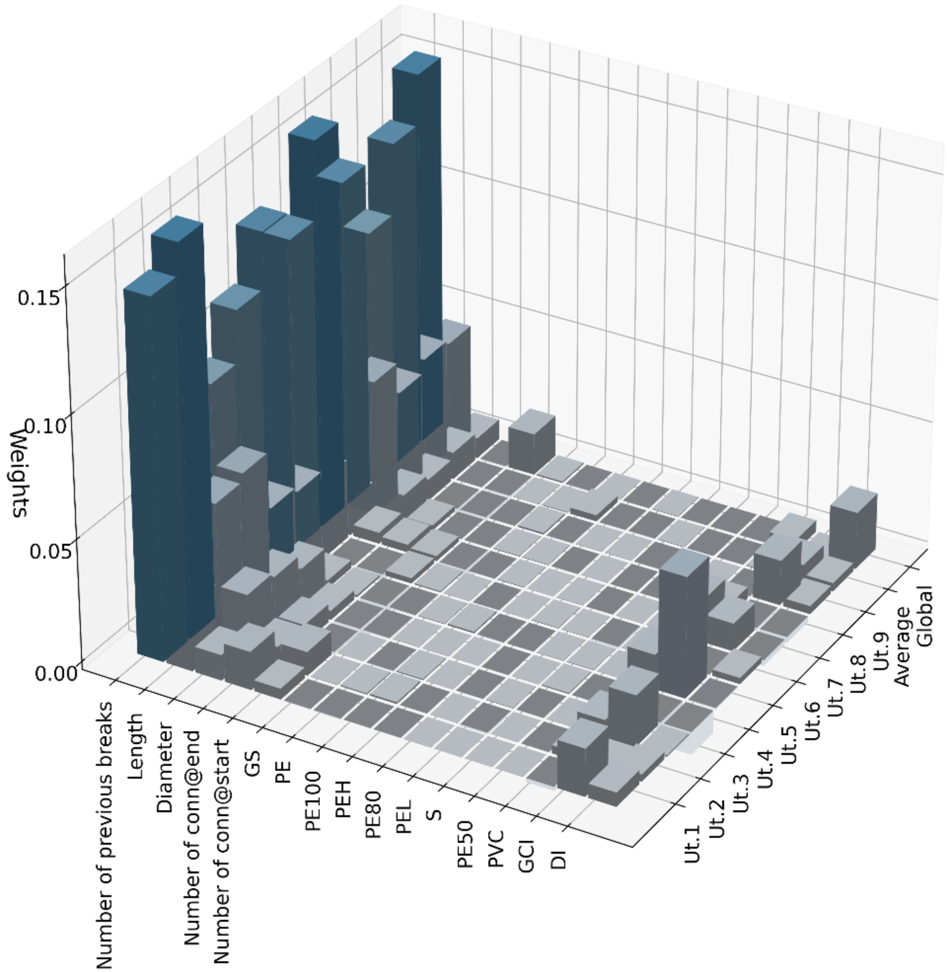
NTNU

Results

Group survival curves



Analysis of feature importance



Number of previous breaks is the most important variable!

Take home messages

- **Proper record of breaks** are important
- Pipe break models **can be transferred** between representative utilities
- **Proper grouping** reduces the uncertainties of group survival curves
- A **previous pipe break is the most dominant indicator** for the time to next break

THANK YOU

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