Optimal Deployment of Smart Meters with Embedded Sensors in Water Networks

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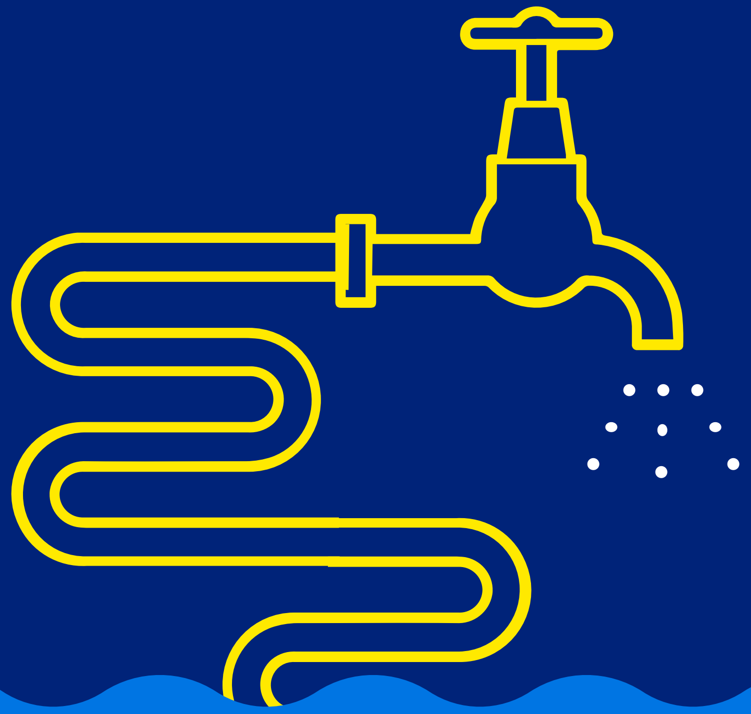
OPTiMA ARC TRAINING CENTRE IN OPTIMISATION TECHNOLOGIES INTEGRATED METHODOLOGIES AND APPLICATIONS

South East Water

MONASH University



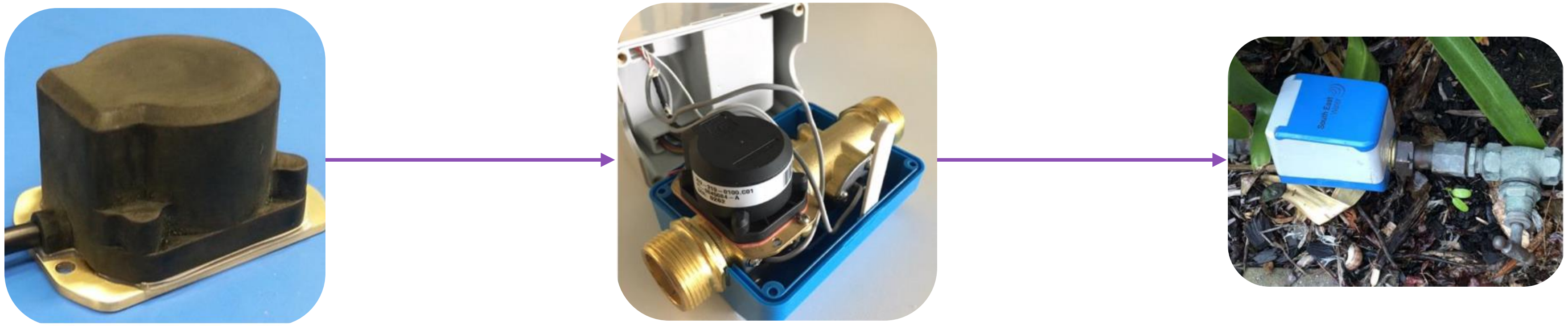
Introduction

Network Leakages

- **Sensor utilization-** detect leakages with sound or vibration produced by leakages
- **Model-based approach-** locates leak locations with mathematical formulas and estimations using hydraulic network models
- **Data-driven approach-** use of signal processing or statistical data for leak detection

(Chan et al., 2018)

Sotto Sensors



- Vibration sensors are placed along with smart meters in each service property (households) in network

(Mofardin et al., 2020)

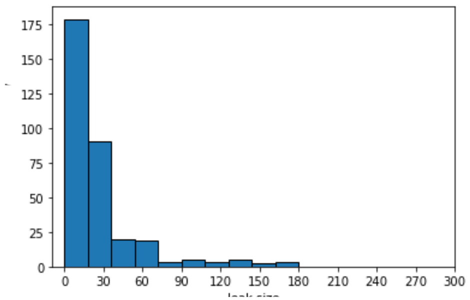
Motivation

Data Sources (Network, Sensor, Leak)

Leak Model

- Uniform leak distribution
- Leak probability of leak based on pipe material type and age.

Frequency

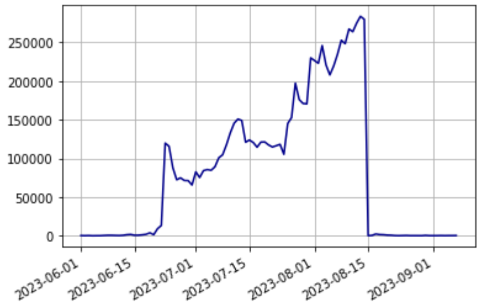


Leak Size

Sensor Model

- How well a certain material conduct sensitivity
- Geometry effects impacting the sensor behaviour

Frequency



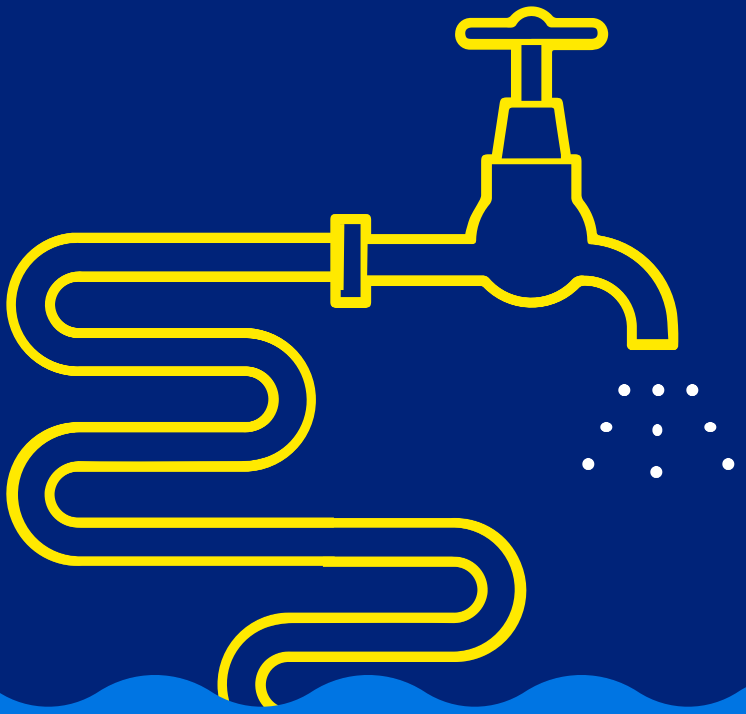
Date

Optimisation Model

Optimisation Models

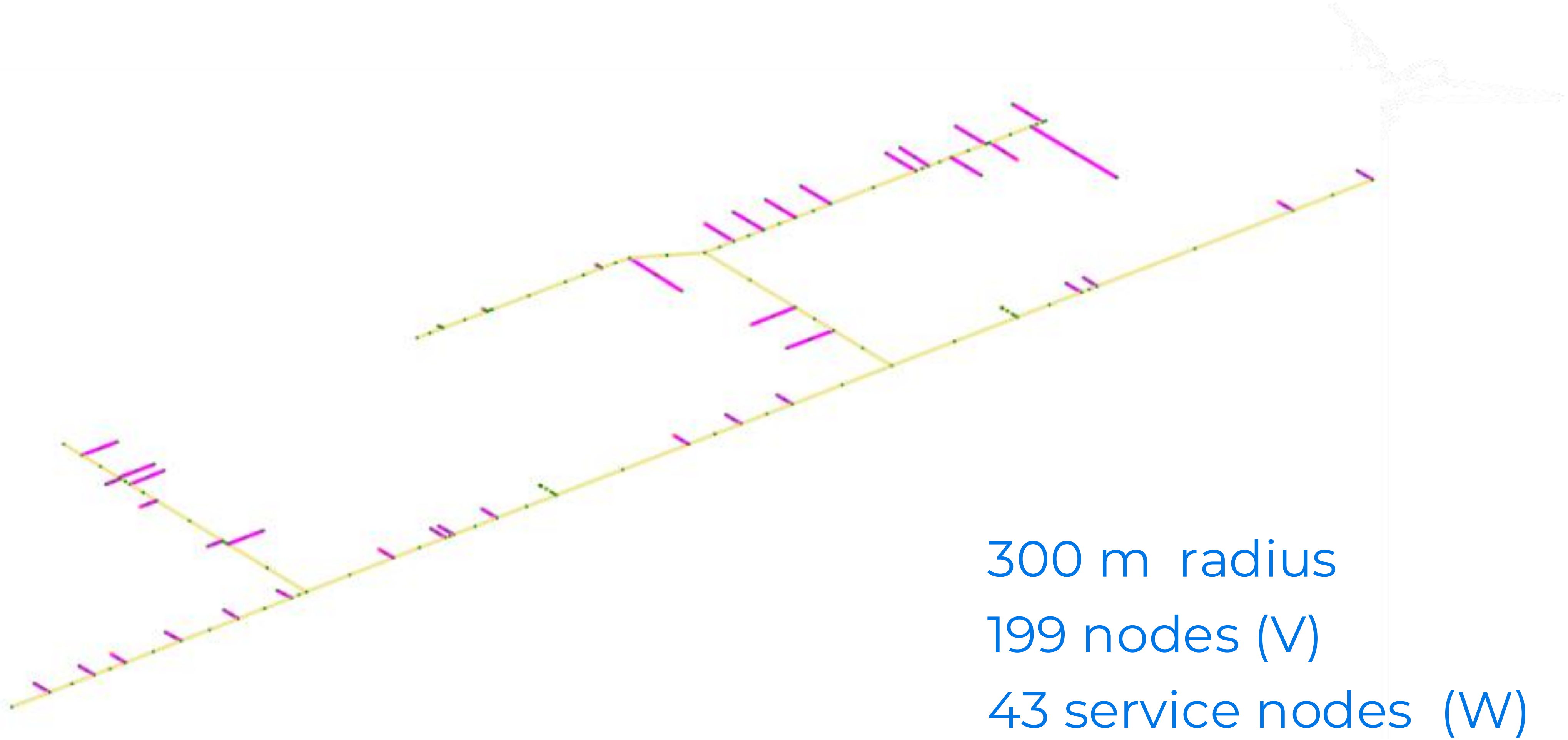
Make the best use of a given situation or resources

Placement of sensor with minimizing the cost of deployment



Optimisation Models

Sample Network



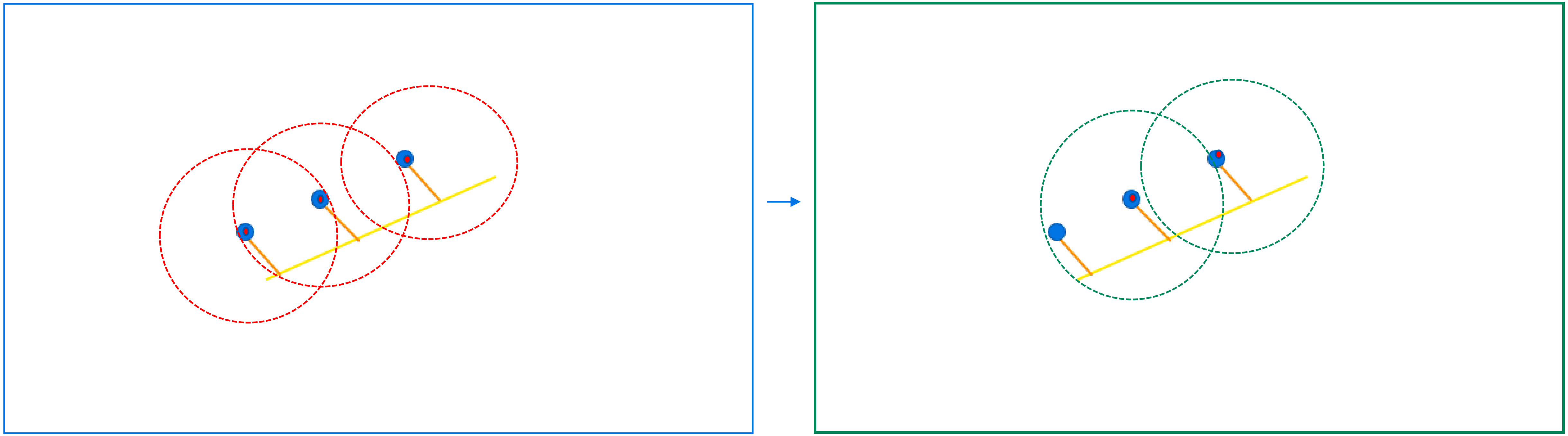
300 m radius

199 nodes (V)

43 service nodes (W)

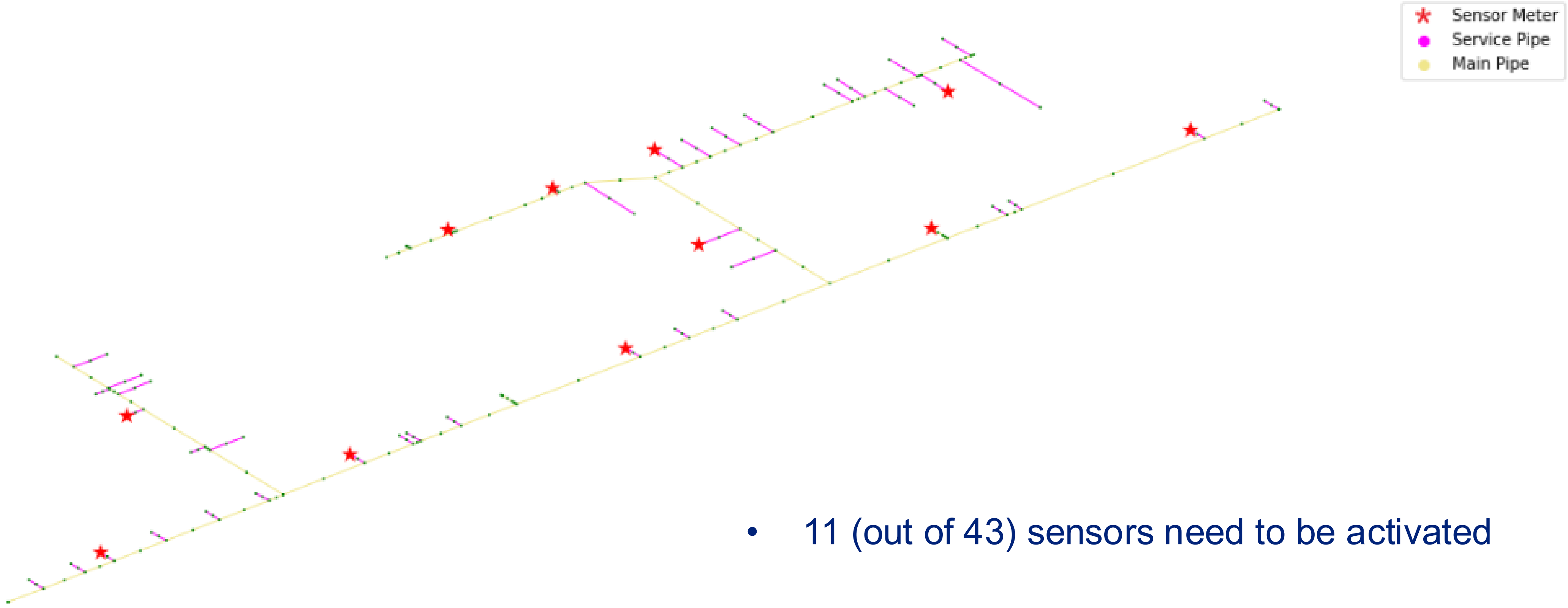
1. Coverage Model

- Covering the network with minimum number sensors
- Assume that each sensor can detect any leaks within a fixed distance d from the sensor



1. Coverage Model Results

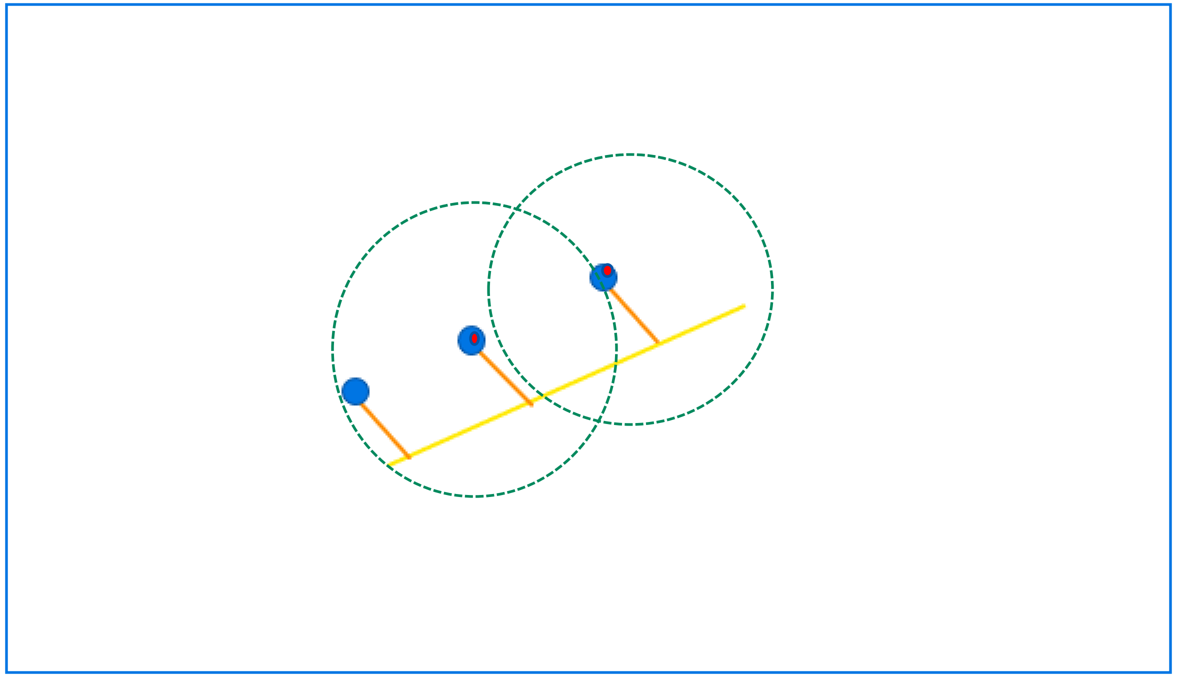
- Covering the network with ***minimum number sensors***
- Assume that each sensor ***can detect any leaks within a fixed distance 30m*** from the sensor

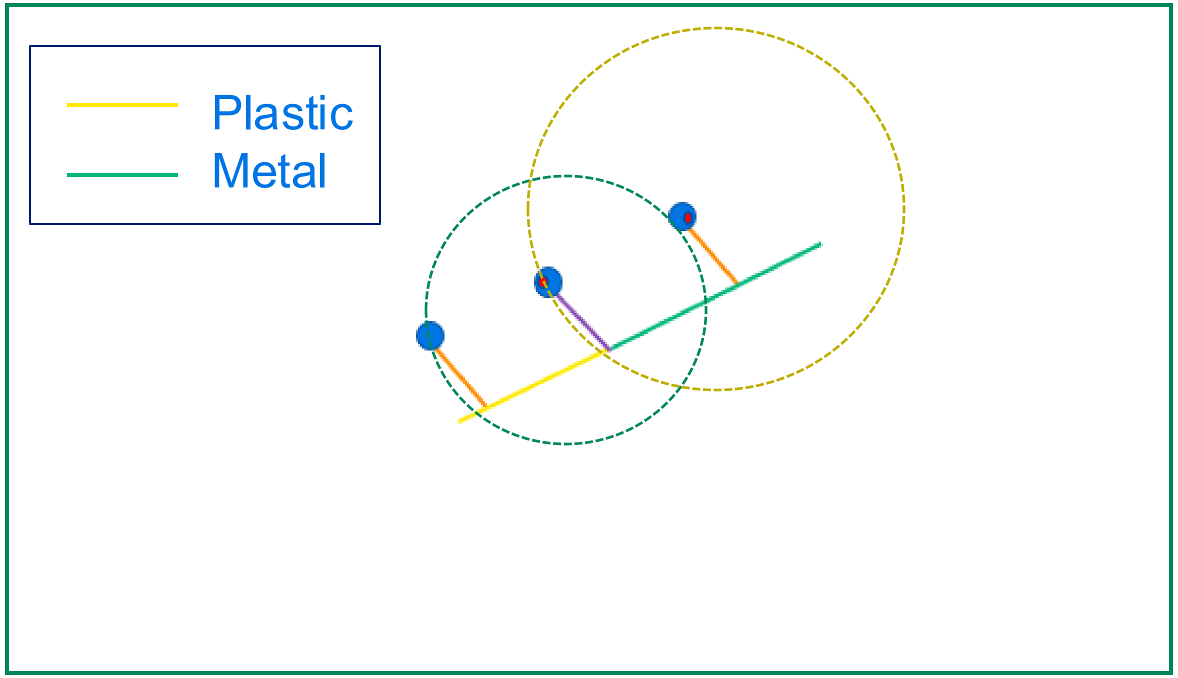


- 11 (out of 43) sensors need to be activated

2. Coverage Model with Sensor Sensitivity

- Covering the network with ***minimum number sensors***
- ***Use sensor sensitivity model*** to determine the converge distance of each respective sensor



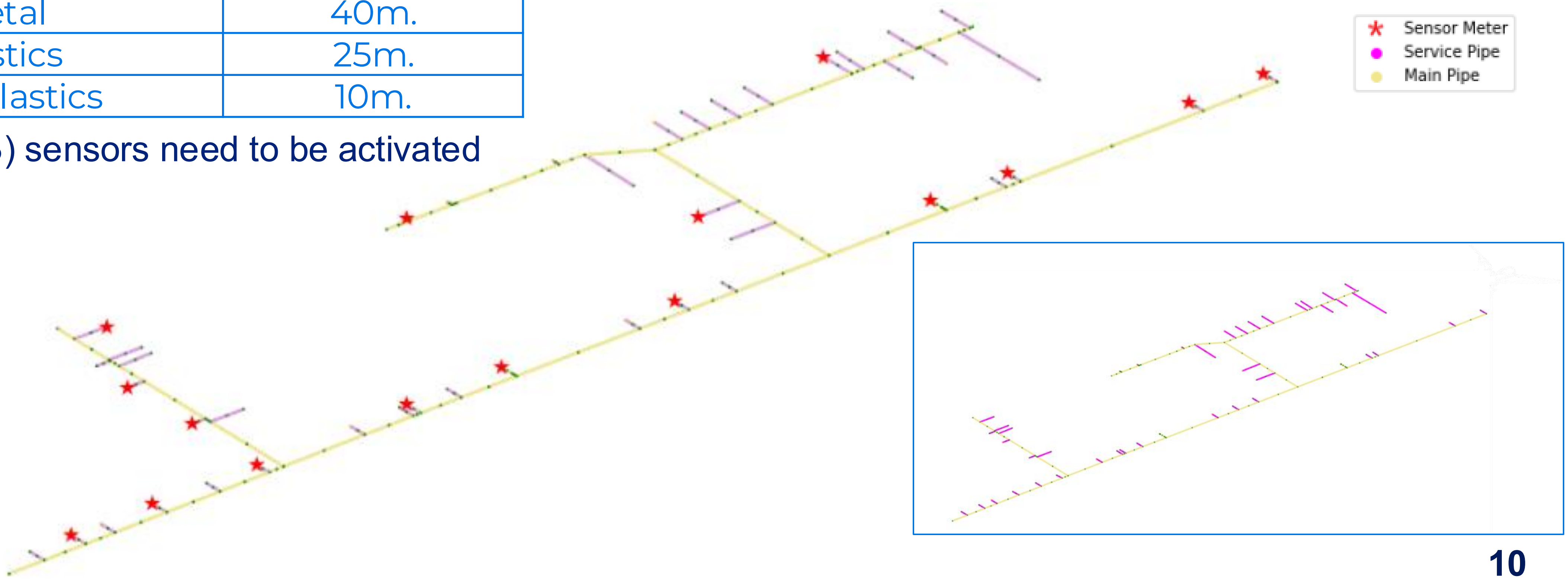


2. Coverage Model with Sensor Sensitivity

- Covering the network with ***minimum number sensors***
- ***Use sensor sensitivity model*** to determine the converge distance of each respective sensor

Leak Size (litres per minute)	***0.2***
Metal	40m.
Plastics	25m.
Non Plastics	10m.

- 16 (out of 43) sensors need to be activated



Stochastic Sensor Placement Model

Objective - minimise combined **cost of sensors placed** & **potentially undetected leaks**

Minimise

$$c_w \sum_{x \epsilon V} l_x \quad + c_s \sum_{z \epsilon W} s_z$$

Input parameters Cost of sensor (c_s) and Cost of water leak (c_w)

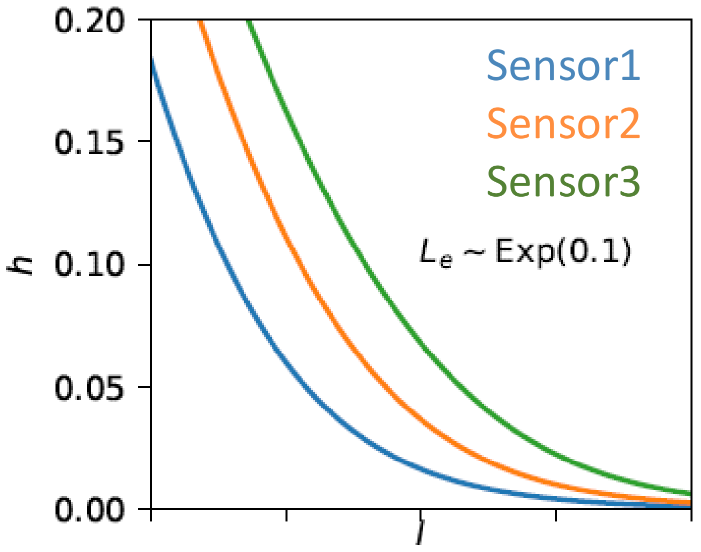
Variables V, W - Nodes & Sensor Nodes / Properties respectively

l_x - Undetected leak of size at node x

s_z - Activation of senor at z sensor node in {0,1}

Failure probability function $h_{z,x}(l_x)$

- expected leak size ***0.2 litres per unit time interval***
- sensor locations with different sensitivities



Probability of no-alarm given a leak of size l_x : $h_{z,x}(l_x) = Pr(A_z = 0, L_x \geq l_x)$

$$= Pr(A_z = 0 | L_x = l_x)\Pr(L_x \geq l_x)$$

Sensor Sensitivity

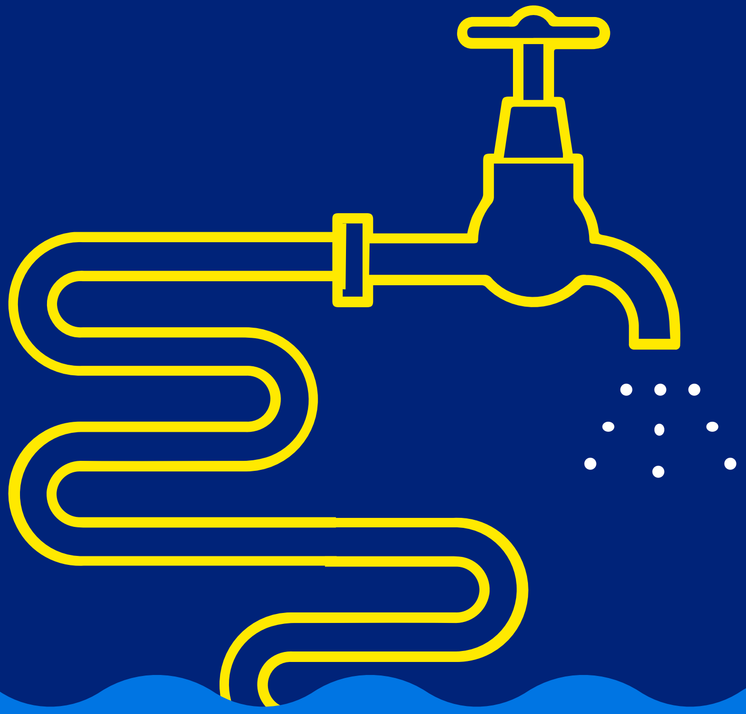
Leak Occurrence

3. Stochastic Sensor Placement Model

Preliminary Results

- Failure probability = 0.05

Input	Output		
Exp Leak Size	*Cost per Year (A$)*	*Sensors*	*Leak Mean*
0.2	4,553,337	43	10.9
0.3	6,754,100	43	16.2
0.5	9,286,430	43	22.2



Conclusion

Conclusion

- **Research Study-** Placement of sensor in cost effective manner to detect maximum amount of leaks in a network

- **Optimisation Models-** Set Cover model is much simpler but Stochastic Sensor Placement Model has potential to minimise the loss of income through undetected water leaks, offset by the cost of the deployed sensors

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Healthy Water.
For Life.

Thank You!

FOR FURTHER INFORMATION

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Extra Slides

Cost Trade-off

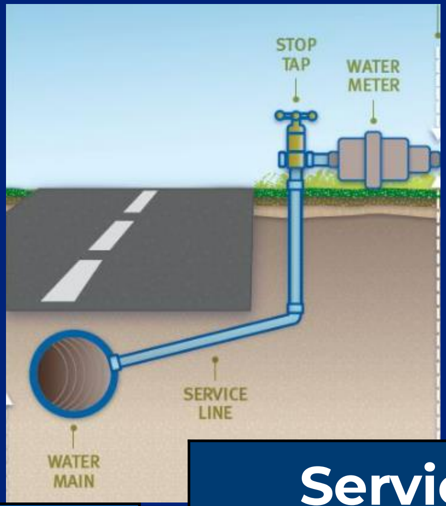
Leaks (l)

Undetected leak cost

Sensors (s)

Cost of sensors

Water Network

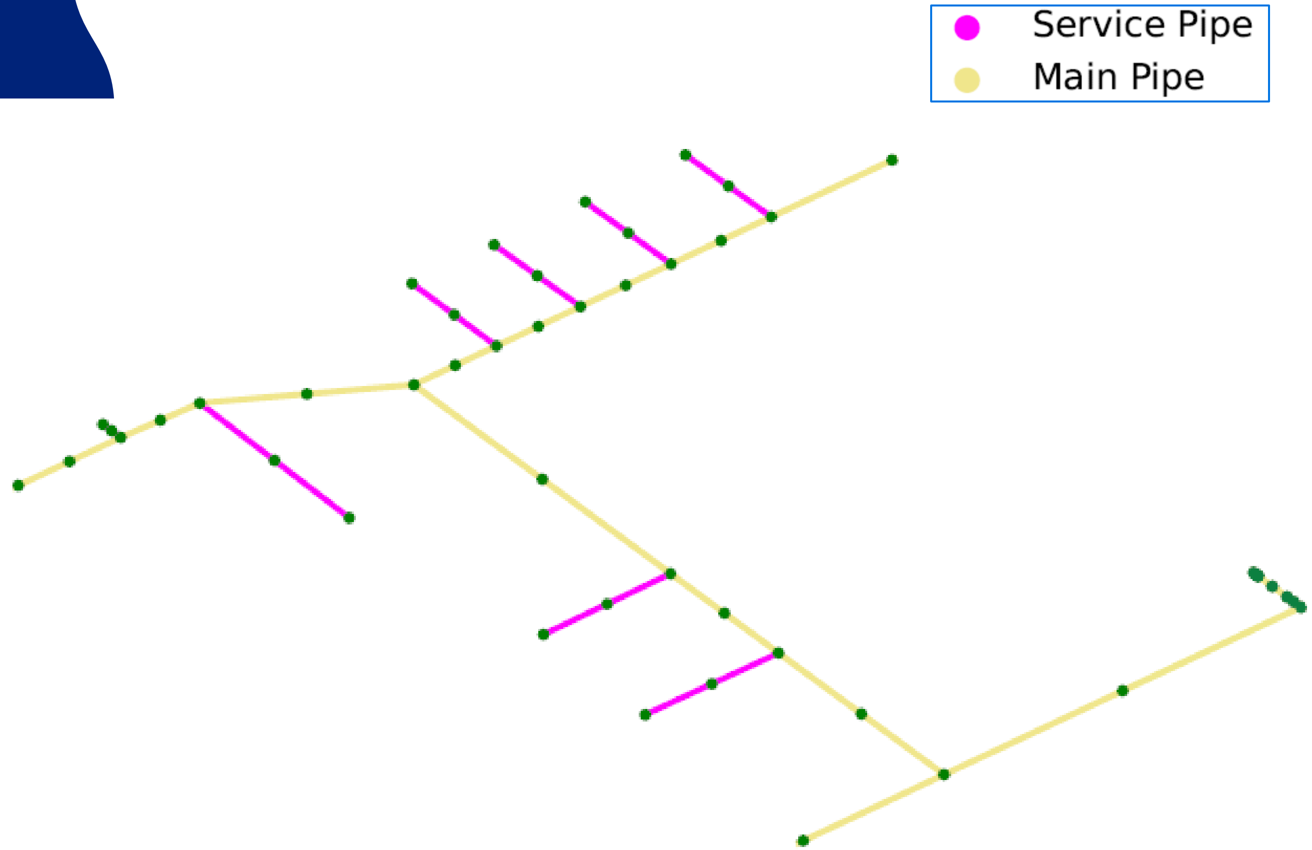


Meter
- *Property (end point)*

Service
- *Pipes*
- *Junctions*

Mains
- *Pipes*
- *Junctions*
- *End point*

Valve
- *junction*

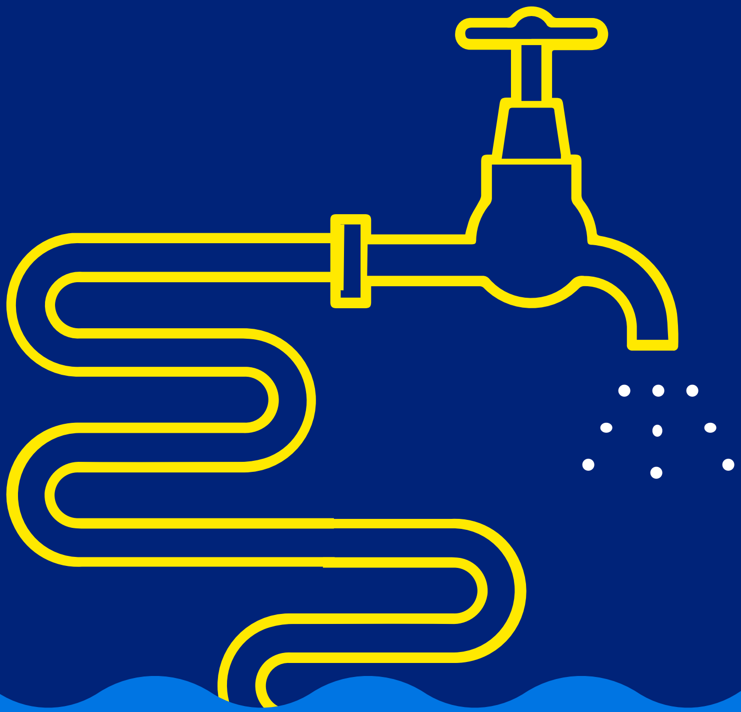


Leakages Summary

15 billion litres of water was lost through leakages, representing 10% of average annual consumption (SEW 2022/23 annual report)

Nonrevenue water losses through the network is around 9% of the utilities' system water input across Australia (Isle Utilities, 2021)

35% of global fresh potable water is lost in distribution networks (Global Water Intelligence, 2023)

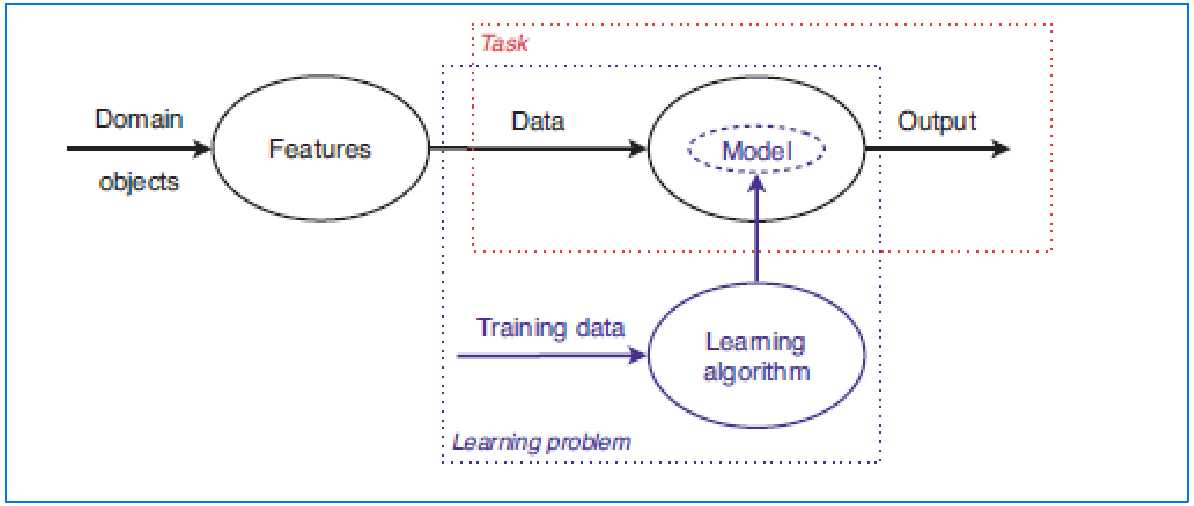


3. Machine Learning Models

Machine Learning Models

"Machine learning is the systematic study of algorithms and systems that improve their knowledge or performance with experience."

-(Flach, 2012)



1. Sensor Sensitivity

Detection of a leak by the sensor

Depends on the sensor detection of vibrations that travel along the pipe material

Model predicts a binary classification with categories alarm or no alarm

Feature variables involve leak size and pipe characteristics along the path of leak location to sensor

2. Leak Occurrence

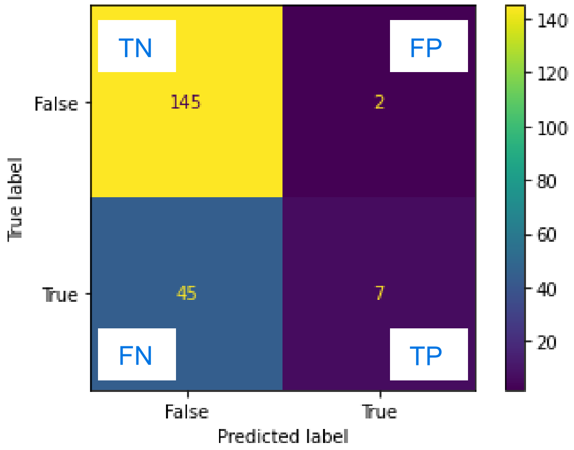
Prediction of a leak based on pipe characteristics

Study the relationship between a leak and pipe features a model which predicts a leak

Fitted model has a binary classification with 1 (when the node has a leak) and 0 (for no leak node) was fitted

Future we plan to fit a model to the predict size of the leak for a given node in pipe

Sensor Sensitivity Model Results

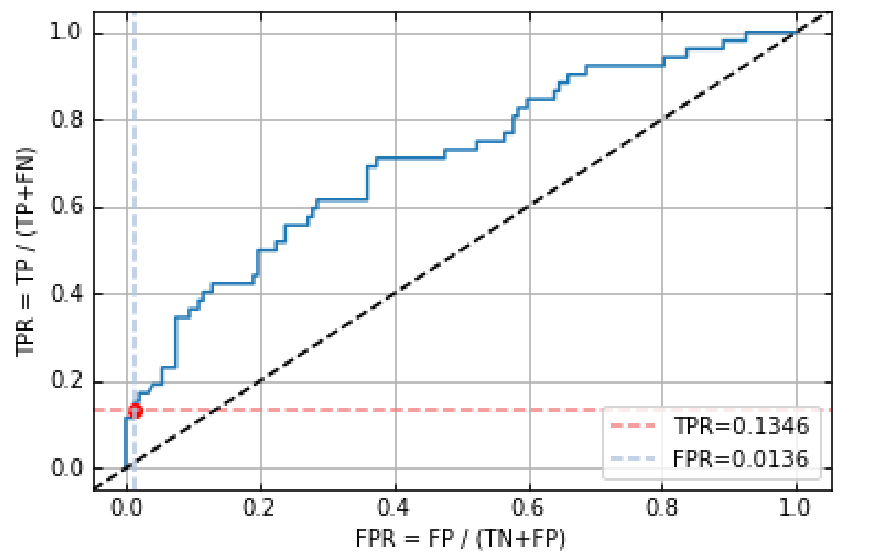


Positive Rate	52 / (147+ 52) = 0.261307
Accuracy	0.764
ROC AUC	0.707

- **TPR (TP / (TP+FN))** is rate of sensor alerts correctly predicted as alerts

- **FPR (FP / (TN+FP))** is rate of non-alerts incorrectly predicted as alerts

- Evaluate performance **of all decision thresholds to modelled probabilities**



Set Cover Model Algorithm

Minimise

$$c_s \sum_{z \epsilon W} s_z$$

V, W - Nodes & Sensor Nodes / Properties respectively

s_z - Activation of senor at z sensor node in {0,1}

c_s - Cost of Sensor

- V × W zero-one matrix, with columns represent potential sensor locations W ⊆ V, while the rows represent all nodes V:

$$x_{i,j} = \begin{cases} 1 : if\ d_{i,j} \leq d \\ 0 : O/W \end{cases}$$

Where $d_{i,j}$ = Distance between i^{th} row node and j^{th} sensor

d = Coverage distance of a sensor

- Assume that each sensor can detect any leaks within a fixed distance *d* from the sensor

2. $h_{z,x}(l_x)$

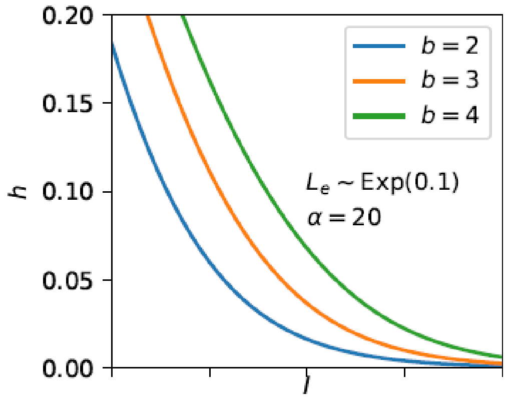
$h_{z,x}(l_x) = Pr(A_z = 0, L_x \geq l_x)$- Probability of not raising an alarm for a leak larger than the undetected leak at node x (l_x) by the sensor z

$$h_{z,x}(l_x) = Pr(A_z = 0, L_x \geq l_x) \leq Pr(A_z = 0 | L_x = l)\Pr(L_x \geq l_x)$$

Sensor Sensitivity

Leak Occurrence

- expected leak size ***0.1 litres per unit time interval***
- sensor locations with different sensitivities- $\{2, 3, 4\}$



2. Probabilistic Sensor Placement M

Minimise

$$c_w \sum_{x \epsilon V} l_x \quad + c_s \sum_{z \epsilon W} s_z$$

Such that

$$h_{z,x}(l_x) \le \varepsilon_x \qquad \forall\, x \in V$$

$$\sum_{x \epsilon V} \varepsilon_x \quad \le \quad \delta$$

Input parameters: Cost of sensor (c_s) , Cost of water leak (c_w) & Overall failure probability (δ)

Variables: V, W - Nodes & Sensor Nodes / Properties respectively

l_x - Undetected leak of size at node x

ε_x - Node x error rate

s_z - Activation of senor at z sensor node in {0,1}

Minimise

$$c_w \sum_{x \epsilon V} l_x \quad + c_s \sum_{z \epsilon W} s_z$$

Such that

$$h_{z,x}(l_x) \le \varepsilon_x \qquad \forall\, x \in V$$

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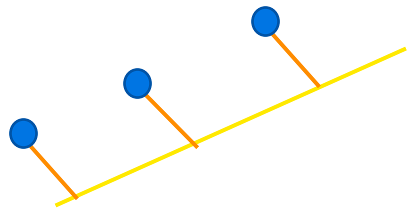

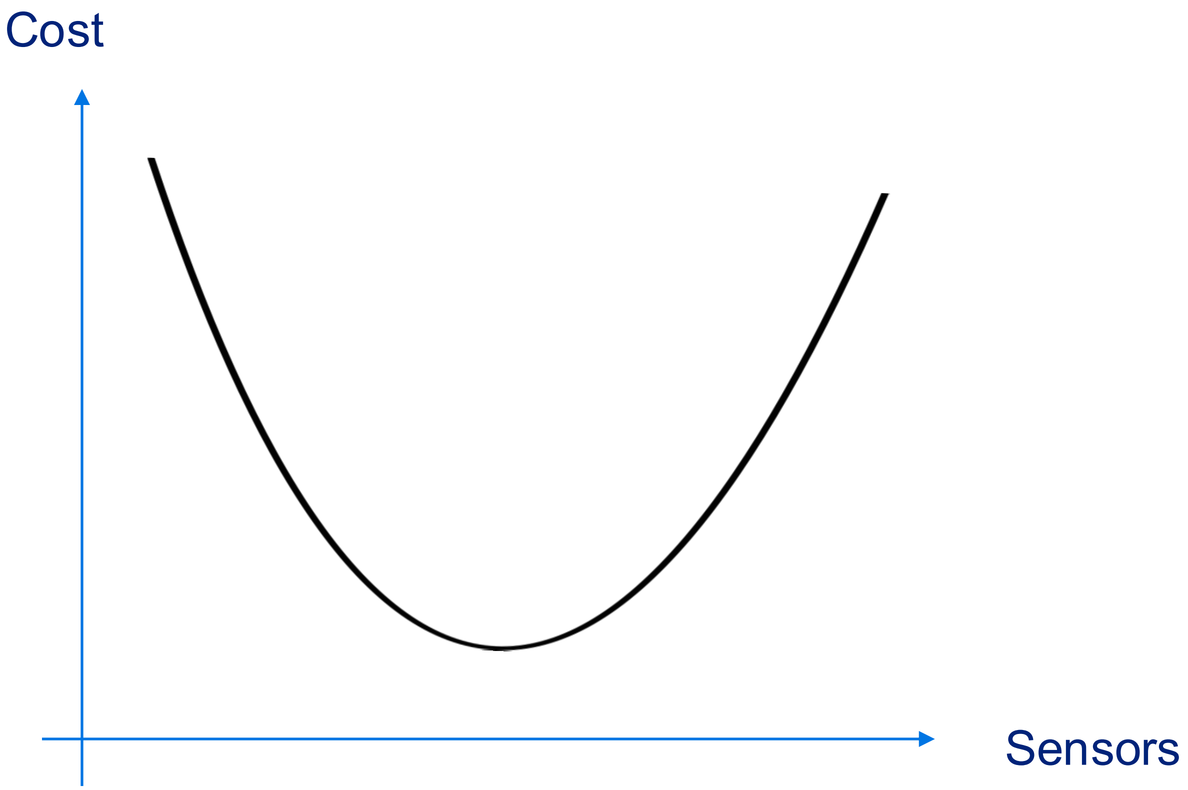
Cost
Sensors