University of Antwerp
Operations Research Group
ANT/OR

The optimization of water distribution networks: a critical review

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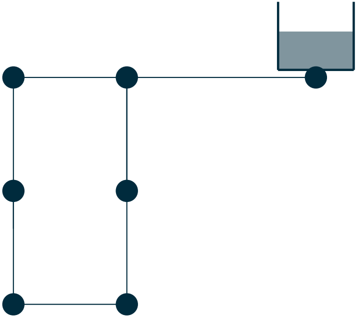
Water distribution networks

Water distribution network (WDN)

A network that consists of different components (pipes, pumps, valves, reservoirs,...) that transport drinking water from one or more resource nodes to multiple demand nodes (domestic, industrial and commercial customers). The water must be supplied in sufficient quantities and at an adequate pressure.



Optimization of WDN

Three different levels:

Table: Optimization levels

decision level	phase	decision variables
strategic	layout	system connectivity, topology
strategic	design	pipe diameter, pipe roughness, ...
operational	operational	pump efficiency, valve control, ...

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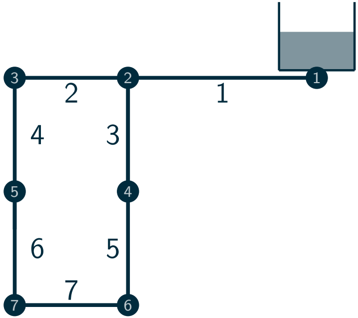
Optimization of WDN

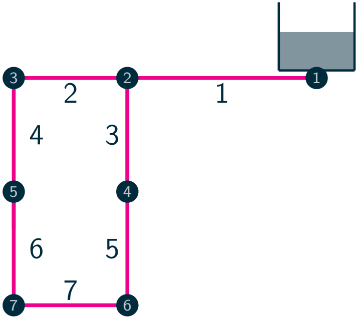
Finding the optimal pipe-configuration out of a set of discrete pipe types in terms of investment cost, with respect to hydraulic principles and conservation laws.

e.g.: three possible pipe types:

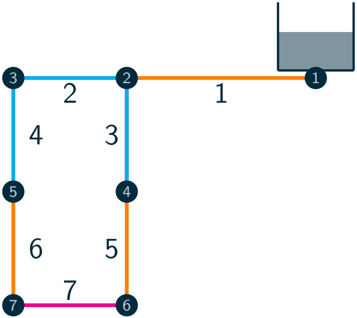
- 1 (diameter=80mm,roughness=130)
- 2 (diameter=80mm,roughness=100)
- 3 (diameter=150mm, roughness=130)



Pipe configurations

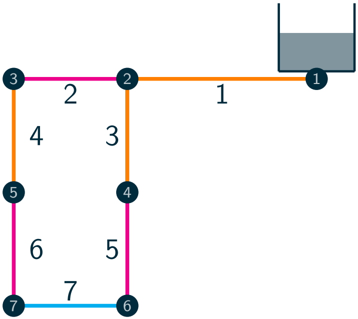


pipe configuration:
P=1,1,1,1,1,1,1

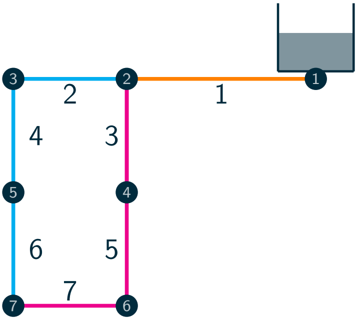


pipe configuration:
P=2,3,3,3,2,2,1

Pipe configurations



pipe configuration:
P=2,1,2,2,1,1,3



pipe configuration:
P=2,3,1,3,1,3,1

Optimization of WDN

Finding the optimal pipe-configuration out of a set of discrete pipe types in terms of investment cost, with respect to hydraulic principles and conservation laws.

$\rightarrow$ discrete decision variable
$\rightarrow$ non-linear objective function
$\rightarrow$ (non-) linear constraint functions

$\Rightarrow$ combinatorial optimization problem

$\Rightarrow$ need for *metaheuristic algorithms*

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Optimization of WDN

An optimally designed WDN:

- has a minimal design cost
- satisfies hydraulic laws
- satisfies mass conservation laws
- satisfies energy conservation laws
- satisfies customer requirements

Objective function

$$\text{Minimize } TC = \sum_{p \in P} (D_p, L_p)$$

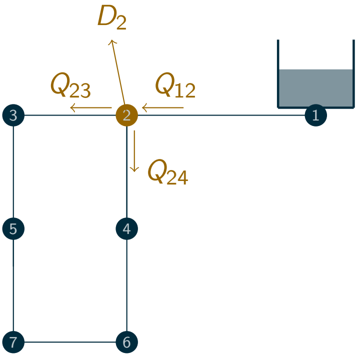
subject to:

$$\forall n \in N : \quad \sum_{i \in N} Q_{in} - \sum_{j \in N} Q_{nj} = D_n - S_n \quad \text{(mass conservation law)}$$

$$\forall l \in L : \quad \sum_{p \in l} \Delta H_p = 0 \quad \text{(energy conservation law)}$$

$$\forall n \in N : \quad H_n \geq H_n^{min} \quad \text{(minimal head requirement)}$$

Mass conservation law



$$\forall n \in N : \quad \sum_{i \in N} Q_{in} - \sum_{j \in N} Q_{nj} = D_n - S_n$$

for node 2 : $Q_{12} - (Q_{24} + Q_{23}) = D_2$

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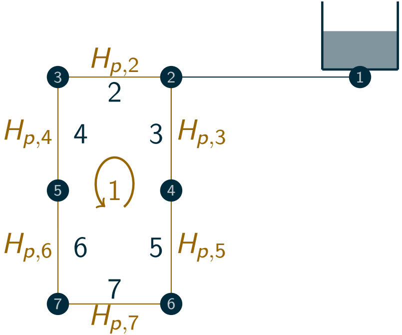
Energy conservation law



$$\forall l \in L : \quad \sum_{p \in l} \Delta H_p = 0$$

$$\text{for loop 1} : H_{p,2} + H_{p,4} + H_{p,6} - H_{p,7} - H_{p,5} - H_{p,3} = 0$$

Objective function

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subject to:

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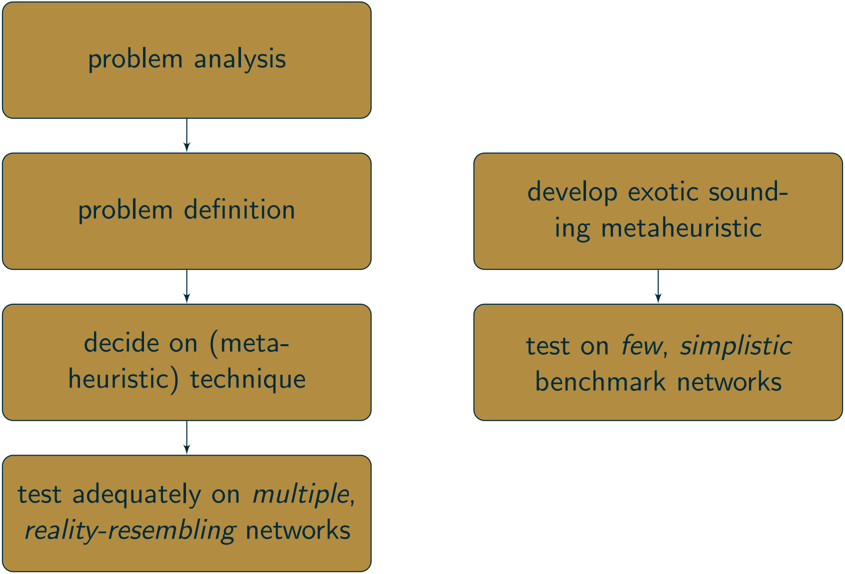
State of the art

- metaheuristics
  - local search
    - selective enumeration
    - simulated annealing
    - tabu search
  - constructive
    - ant colony optimization
    - particle swarm
    - particle swarm harmony search
  - evolutionary
    - genetic algorithm
    - memetic algorithm
    - cross entropy
    - scatter search
    - immune algorithm
    - shuffled frog leaping algorithm
    - differential evolution

State of the art



State of the art

problem analysis

↓

problem definition

↓

decide on (meta-heuristic) technique

↓

test adequately on *multiple*, *reality-resembling* networks

problem analysis?

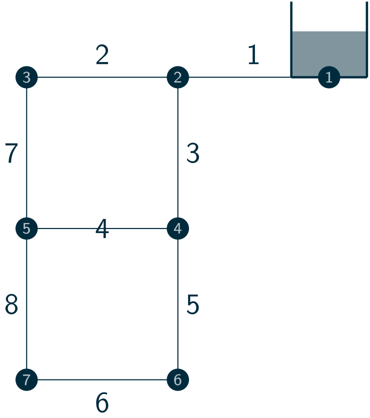
problem definition?

develop exotic sounding metaheuristic

↓

test on *few*, *simplistic* benchmark networks

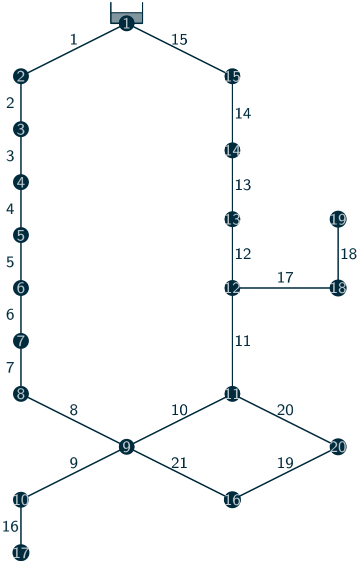
Two loop network (Alperovits & Shamir, 1977)



- 6 demand nodes
- 1 reservoir node
- 8 pipes
- 2 loops

Benchmark networks

New York City Tunnels (Schaake & Lai, 1969)

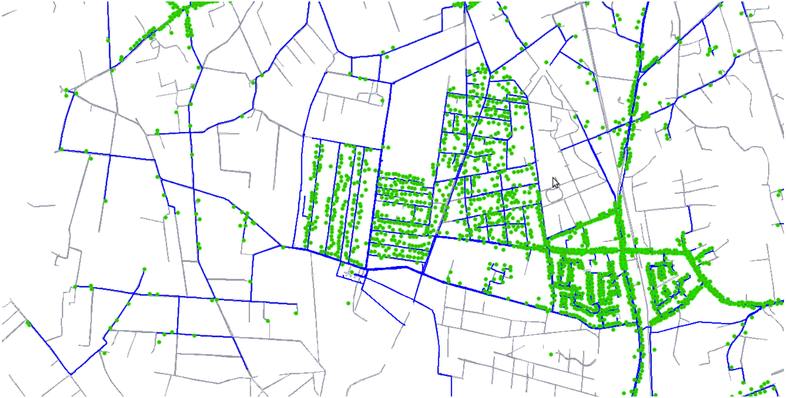


- 20 demand nodes
- 1 reservoir node
- 21 pipes
- 2 loops

Realistic network

Realistic network

Realistic network



Comparison of networks

Table: Dimensions of benchmark and realistic networks

	Two loop	New York	Hanoi	realistic network
junctions	7	20	32	j
loops	2	2	3	(6,166 + 1 - j)
pipes	8	21	34	6,166
cost function	1	1	1	1
available pipes	14	16	6	90
equations	**18**	**44**	**70**	**12,334**
solution space	$14^8 = 1.476 \times 10^9$	$16^{21} = 0.193 \times 10^{26}$	$6^{34} = 2.865 \times 10^{26}$	$90^{6,166} = 5.301 \times 10^{10,826}$

State of the art on NYCT

Overview of results: NY City Tunnels problem by Schaake and Lai, 1969

Method	Authors	hydraulic *w* coefficient	F/IF under EPANET2?	Total Cost (in mUSD)
Tabu Search 1	Cunha and Ribeiro, 2004	na	IF	37.13
Tabu Search 2	Cunha and Ribeiro, 2004	na	IF	37.13
Genetic Algorithm	Savic and Walters, 1997	10.5088	IF	37.13
Genetic Algorithm	Lippai et al., 1999	10.5088	IF	38.13
Simulated Annealing 1	Cunha and Sousa, 2001	10.5088	IF	37.10
Scatter Search	Lin et al., 2007	10.5088	IF	36.68
Immune Algorithm	Chu et al., 2008	10.5088	IF	37.13
modified Immune Algorithm	Chu et al., 2008	10.5088	IF	37.13
Ant Colony Optimization	Maier et al., 2003	10.6668	F	38.64
Shuffled Frog Leaping Algorithm	Eusuff and Lansey, 2003	10.6688	F	38.80
Ant System	Zecchin et al., 2005	10.6688	F	38.64
Max-Min Ant System	Zecchin et al., 2006	10.6688	F	38.64
Harmony Search	Geem, 2006	10.6688	F	38.64
Particle Swarm Harmony Search	Geem, 2009	10.6688	F	38.64
Differential Evolution	Vasan2010	10.6668	F	38.64
Scatter Search	Lin et al., 2007	10.675	F	38.64
Simulated Annealing 2	Cunha and Sousa, 2001	10.6792	IF	38.80
Genetic Algorithm	Savic and Walters, 1997	10.9031	F	40.42
Simulated Annealing 1	Cunha and Sousa, 2001	10.9031	IF	40.40
Scatter Search	Lin et al., 2007	10.9031	F	40.42
Immune Algorithm	Chu et al., 2008	10.9031	F	40.42
modified Immune Algorithm	Chu et al., 2008	10.9031	F	40.42

Our simple algorithm on NYCT

Step 0. Sort
Sort pipes according to decreasing pipe length

Step 1. Set diameters on max
Set all pipe diameters on maximum
→ maximal cost
→ hydraulic feasible

Step 2. Two local search mechanisms
1. Iteratively decrease
2. Iteratively increase + decrease

Step 3. Perturbation
Set random selected pipes on maximum

→ also led to reported minimal cost 38.64 mUSD (EPANET 2)

State of the art

Shortcomings earlier developed methods:

- Methods not based on established principles of metaheuristic design
- Heuristics are case-specific
- Methods are not adequately tested

Therefore, heuristics are not applicable on real networks

Need for:

- Correctly designed metaheuristics that can be used in real-life situations
- High-quality networks on which developed methods can be adequately and profoundly tested

Network generation

Develop a method to generate realistic WDN

Characteristics:

- algorithmic generation $\rightarrow$ networks of different sizes and characteristics ($\sim$ realistic networks)
- free and online available
- EPANET-format

Objective:

- extensive library should become new benchmark
- stimulate development of more effective optimization methods

Thank you for your attention!

Any questions?

Slides available at `http://webhost.ua.ac.be/antor/`

Contact via annelies.decorte@ua.ac.be