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Decision Support Tool For Hydraulic Reliability Based Design Of Water Distribution Networks

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DECISION SUPPORT TOOL FOR HYDRAULIC RELIABILITY BASED DESIGN OF WATER DISTRIBUTION NETWORKS

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The reliability analyses conducted on geometric-, hydraulic- and economic grounds all reflect the complexity of network resilience that is still difficult to generalize or classify, as well as it is impossible to asses without full integration of all three aspects. The proposed decision support tool for design and hydraulic reliability assessment of water distribution networks aims to achieve this integration processes for a preselected seed of network sources and (demand) nodes prepared in EPANET without any pipe connection. The tool is composed of the modules for network layout generation by applying the principles of graph theory, the filtering, initialization, and standard optimization based on the least-cost selection of diameters. Furthermore, the diagnostics will be conducted for all generated layouts, as well as the network reliability can be assessed by applying different resilience indices known in literature. The tool has been illustrated on a design example of 50-node network analyzing 13,000 generated layouts for the selected demand scenario. The results for all the networks present the network resilience against the total cost that includes investment, operation and maintenance, leaving freedom to the user to decide about the final layout.

INTRODUCTION

Design of water distribution networks aims at solutions that will guarantee acceptable service levels. The common understanding of the word 'acceptable' will depend on the availability of water, needs and habits of consumers and their ability and willingness to pay for it. Until 15-20 years ago, the issues of water quality and network hydraulic reliability were less considered due to absence of powerful methods and tools for such analyses. The IT revolution has significantly changed such a practice, whilst the awareness of consumers about their service levels has grown in parallel, practically all over the world. The result of this has been a more stringent design process with significantly sharpened economic and reliability considerations. The quality of the analyses has improved, which eventually enabled more insight into irregular supply scenarios. Consequently, the safety factors applied in the design could have been scrutinized once the accompanying costs have been compared with the network performance in stress situations.

The aim of any network design is to provide conveyance of sufficient water quantities and then to preserve the water quality obtained at the source i.e. after the treatment process has taken place. Trifunović [9] states two postulates of water distribution network hydraulic design: (1) 'Water flows to any discharge point choosing the easiest path: either the shortest one or the one with the lowest resistance.' and (2) 'Optimal design from the hydraulic perspective results in a system that demands the least energy input for water conveyance.' In practice, this means:

1. maximum utilisation of the existing topography (gravity),
2. use of pipe diameters that generate low friction losses,
3. as little pumping as necessary to guarantee the design pressures, and
4. valve operation reduced to a minimum.

Hydraulic design parameters mostly concern pressures, hydraulic gradients and pipe velocities. There is no universally acceptable pressure range. For instance, The Office of Water Services OFWAT [3] in England specifies that pressures of seven meters water column (mwc) above street level can be considered as the minimum acceptable standard, below which the consumers may be entitled to compensation for unsatisfactory service. The practice of many water companies in The Netherlands is to maintain the minimum pressures around 20 mwc allowing temporary drops in irregular situations to around 10 to 15 mwc. Tanyimboh *et al.* [7] indicate the required minimum service pressure to be as high as 25 mwc, to allow for possible increases in the demand. That is more or less sufficient to supply a standard building without internal boosting installation, which in most urban areas is three to five floors high. The maximum pressure in the network should normally be around 60 to 70 mwc. According to Chase [1], the pressures during normal operations should be kept above 20 mwc and below 70 mwc.

Hydraulic gradients tell something about the network conveyance i.e. the balance between the energy input and energy loss and as such, the balance between the investment and operational costs. They eventually reflect whether the minimum pressure in the network has been created through increased pumping or enlarged pipes, which also has the implications on network resilience against the whole economy of water distribution. Trifunović [9] suggests the following values as a rule of thumb: 5-10 m/km, for small diameter pipes, 2-5 m/km, for mid-range diameter pipes, and 1-2 m/km, for large transportation pipes. Finally, the velocity range is also to be assessed in the network design process. Too low velocities have potential implications for water quality (sediment accumulation, low chlorine residuals, increased corrosion), while too high velocities are mostly corresponding to high hydraulic gradients, indicating exceptional head-losses. The recommended design values are: ± 1m/s, in distribution systems, ± 1.5 m/s, in transportation pipes, and 1-2 m/s, in pumping stations.

Ideal matching of the recommended design values will mostly depend on the topographic conditions that are the crucial factor for determination of supply scheme. The design parameters will further be influenced by the pipes' condition.

NETWORK DESIGN AND RELIABILITY ASSESSMENT TOOL

The **ne**twork **d**esign and **r**eliability **a**nalysis tool (NEDRA) has been developed to facilitate design process of water distribution networks by adding more of reliability assessment perspective to it. The programme has been coded in Microsoft Visual C++ 2010 Express, using EPANET toolkit library to communicate with EPANET software of US EPA Rossman [6], 2000). The integrated optimiser is the Evolving Objects (EO), which is a single objective oriented GA-optimization tool developed by Keijzer *et al.* [2]. NEDRA consists of five main modules dealing with network (1) generation, (2) filtering, (3) initialisation, (4) optimisation and (5) diagnostics. The required input for the tool is an arbitrary seed of network sources and (demand) nodes prepared in EPANET without any pipe connection (*.inp).

Network generation module

The network generation module has been developed applying the concepts of graph theory, which is elaborated in Trifunović *et al.* [10]. To avoid configurations that are uncommon in reality, the following four principles have been built into the algorithm: (1) to respect the maximum defined number of nodal connections, (2) to give priority to the closest available node for connection, (3) to avoid crossings between pipes without connecting them, and (4) to avoid pipe duplication that could occur by connecting the same nodes in reversed order. These principles have implications on the way the graph matrices are manipulated during the programme execution. For the sake of consistency, the generated networks are exclusively simple graphs i.e. do not have parallel pipes; those should be added manually afterwards, if necessary. The networks can be generated non-randomly, by sequential manipulation of the matrices and choosing amongst different levels of complexity, or entirely randomly. The generation process will be followed by the network screening where the integrity of the generated layouts is checked, and finally by assigning of the network properties that should enable running of snapshot hydraulic simulation; uniform or random selection of the pipe diameters and roughness will be applied just to provide the completeness of the file, while the pipe lengths can be calculated by using the nodal coordinates from the input file.

Network filtering and initialization

The network filtering module compares all generated and screened network layouts with the network template prepared to suggest the preferred or the only possible routes i.e. the streets. The degree of similarity with the template file will be summarised in the specified output text file. This file lists the number of links in each of the generated networks and the number of those that match the template. The IDs of the mismatch links will be shown in the networks that have less than ten of these. Finally, the list of all names of the files that match the template will be printed at the end. The user can also decide to add the networks below certain number of mismatched links to this list, qualifying them as 'passed'. The rest of the files will be eliminated from further analyses. Following this step, the network initialisation module helps to further modify the model input by comparing the content of the qualified files with the template used for the filtering of generated files. The template is a network whose basic properties can be assigned to the generated networks if this was not done during the process of generation, or their data have been modified in the course of various analyses, for instance during the optimisation. The data conversion will also include pumps and valves if existing in the template. This module can therefore be run before or after the optimisation.

Network optimization and diagnostics

The goal of the optimization module is to get optimal solutions for the network pipe diameters. The main reason to use the EO-optimiser has been the fact that it is an open source package for evolutionary computations, which can be adapted for specific research purposes and used for relatively large number of nodes and links in a network. Furthermore, an investigation on the best performing GA-optimiser to be built into NEDRA was not an objective of this research. The qualified networks will be optimised to keep the selected threshold pressure at each demand node assuming the least-cost combination of diameters selecting from the list prepared in one of the following three ways: (1) by specifying a continuous range, (2) by specifying a range and the diameter increment, and (3) by specifying the number of specific diameters manually. Final output from the simulation is (a sequence of) optimised INP-file(s) named based on the above selected approach. Finally, the network diagnostics module analyses geometric and hydraulic properties, both in demand driven (DD) and pressure-driven demand (PDD) mode, of a network or sequence of networks. It further assesses the network resilience using two measures: the available demand fraction (*ADF*) of Ozger and Mays [4], and the network resilience index (I_n) of Prasad and Park [5] based on Todini [8], which are both put in the prospect of the total costs of investment and operation and maintenance. A selection can be made between the calculations where detailed results will be given for one specific scenario, by tabulating all the pipes. Alternatively, a particular network parameter can be modified in number of incremental steps, defining the multipliers in similar way as it is done in EPANET with the general multiplier. In addition to the uniform multipliers, a feature has been added to specify a range of randomised multipliers for number of parameters. The full list of options is shown in Figure 1.

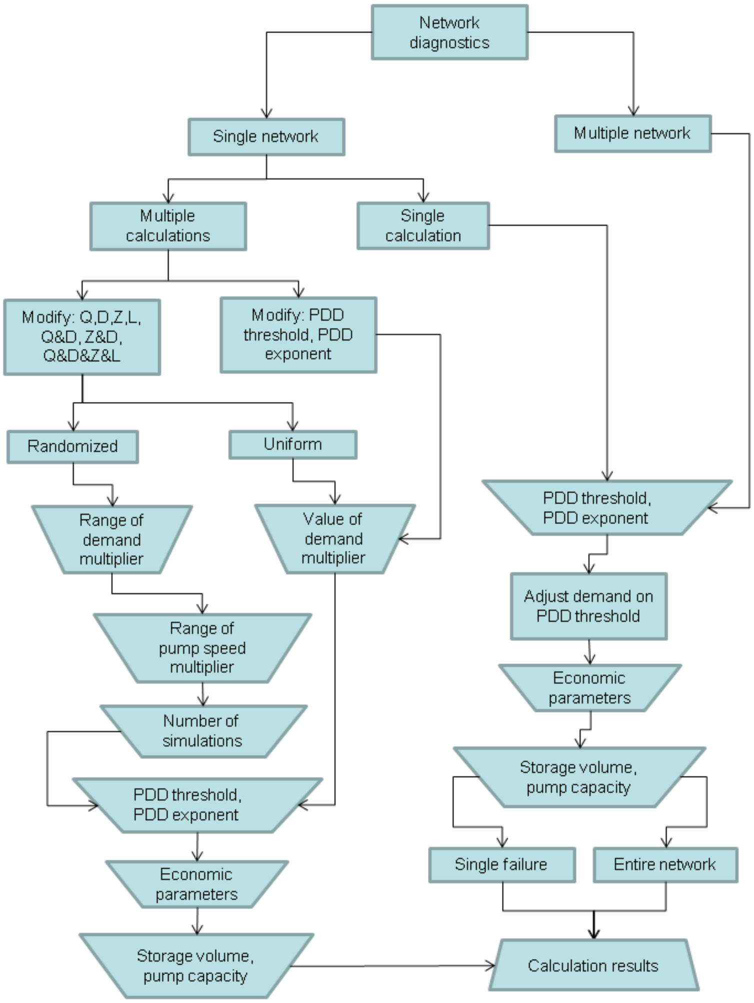

Figure 1. Menu structure in the network diagnostics module

CASE STUDY

NEDRA has been illustrated on a synthetic case of a reservoir and 50 demand nodes, prepared in EPANET as shown in Figure 2. The case reflects a gravity supply situation on a terrain descending from the reservoir in the upper left corner, for some 45 m. The total demand of 305 l/s is distributed over relatively wide area within the distance to the most faraway node of roughly 16 km from the source, calculated based on the nodal coordinates. The head of the reservoir is 50 msl. The small figure on the right shows the hypothetical template that resembles preferred connections e.g. street routes.

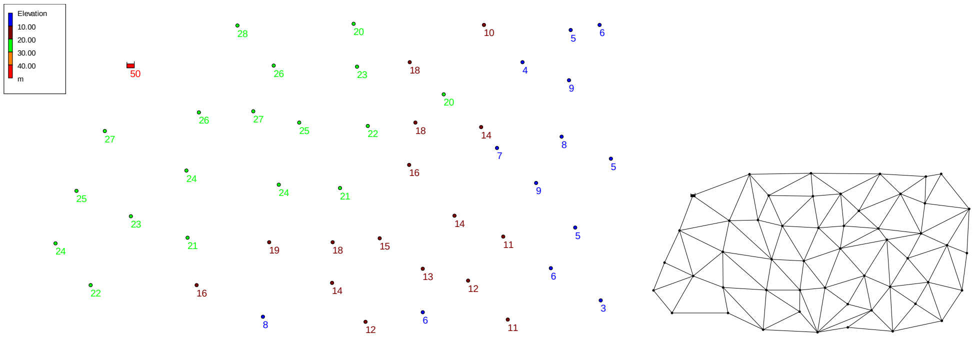

Figure 2. EPANET seed of nodes processed by NEDRA - elevations (msl); small - the template.

Total 13,000 layouts were produced by the network generation tool. The first 3000 networks have been generated in 30 batches of 100 layouts applying different connectivity settings, both random and non-random. This was done to explore the type of layouts, the generation time, and the overall robustness of the tool. The settings in the five batches with the best match to the template were then used to generate another 1000 layouts each, and finally the settings of the best match of these five batches were again used to generate additional 5000 layouts; the latter run took about eight hours using a standard laptop.

To provide a variety of layouts, all five batches were filtered allowing up to three links not matching the template: the batch of 5000 layouts and four previous batches of 1000 layouts, each. The GA-optimisation was conducted for all filtered networks using the following diameter range (in mm): 80, 100, 125, 150, 200, 250, 300, 350, 400, 450, 500, 600, 700, 800, and 1000, and at the proportional unit costs. Total 1817 filtered networks ranging between 55 and 79 pipes were optimised in less than seven hours, as shown in Table 1.

Table 1. Overview of GA-optimized networks

Batch code	Total filtered networks	Number of non-matching links	Optimization time (min)
R55-75/U/5k	409	3	97
NC2/4/1k	477	0	91
NC4/U/1k	252	1	64
N55-75/C2/4/1k	375	0	75
N55-75/C4/U/1k	304	1	77

The explanation of the codes in the table is as follows: R/N - random/non-random generation, 55-75 - the selected range of links, C2/C4 - the layout complexity level, U - unlimited number of connections to each node, 4 - maximum four connections allowed to each node, 5k/1k – the9 batch of 5000/1000 generated layouts, respectively. Trifunović *et al.* [10] gives more insight into this terminology and the process.

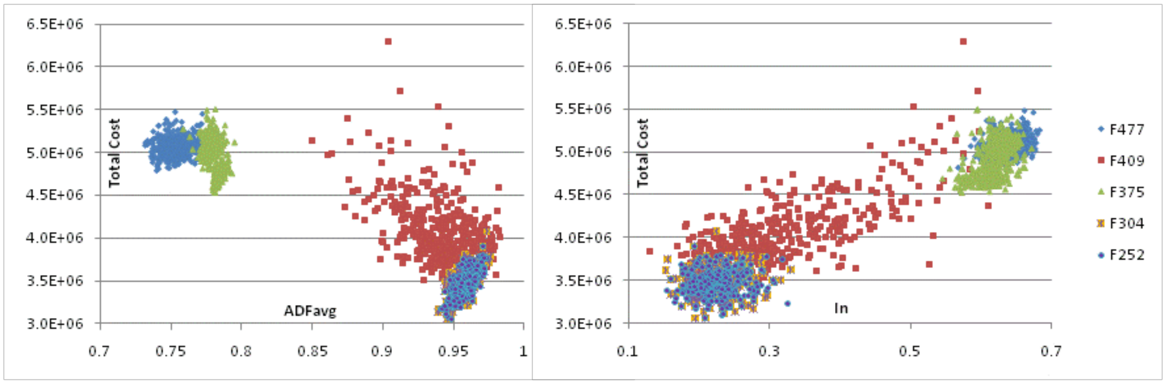

Figure 3. Network resilience vs. the total cost: left - ADF_{avg}, right - I_n

The analysis of the network resilience done by the network diagnostics tool has been shown in Figure 3; the total cost has been derived based on the annual recovery method for the loan repayment of 25 years at 8% interest rate, while the O&M costs have been assumed as a certain percentage of the investment costs, namely 0.5%. The discrepancy in the results can be explained by the nature of the indices: while the ADF_{avg} is based on the PDD hydraulic simulations showing true loss of demand, the dominant parameter of I_n is the surplus head, which has been kept relatively low in the gravity supply. The ADF_{avg} shows those networks with low I_n values to be resilient due to well developed connectivity between the nodes. Table 2 therefore shows the selected networks in the three batches with higher ADF_{avg}; the values in bold show the absolute maximum/minimum values, regardless the batch.

Table 2. Overview of selected networks

Net code	Batch code	Property	Cost (10^6)	p_{min}-p_{max} (msl)	ADF$_{avg}$	I_n
1727	R55-75/U/5k (F409)	Cheapest	3.46	19.86 - 36.69	0.945	0.237
4611		Least reliable	5.13	18.58 - 44.08	**0.850**	0.564
3765		Most expensive	**6.29**	18.13 - 45.67	0.938	**0.575**
3307		Most reliable	4.00	20.01 - 38.28	**0.983**	0.363
691	NC4/U/1k (F252)	Cheapest	**3.06**	19.64 - 31.70	0.948	0.209
081		Least reliable	3.17	20.03 - 34.74	0.941	0.196
508		Most expensive	3.90	19.85 - 32.24	0.971	0.192
757		Most reliable	3.76	20.06 - 35.85	0.974	0.262
353	N55-75/C4/U/1k (F304)	Cheapest	**3.06**	19.83 - 30.90	0.946	**0.194**
760		Least reliable	3.13	19.89 - 35.65	0.939	0.251
218		Most expensive	4.07	19.96 - 33.45	0.974	0.224
962		Most reliable	3.78	19.47 - 34.90	0.976	0.272

The cheapest and the most reliable network in each group were further diagnosed on the impact distribution of the worst case failure (ADF_{min}). Table 3 shows the percentage of nodes with their own *ADF* classified in ten categories. The least affected networks are 3307 and 962 where 60 and 50% of the nodes would have lost less than 20% of their original demand in the scenario of the worst case failure, while 6 and 12% would have lost more than 60% of their original demand, respectively (shown in bold). In case of network 1727, all nodes will lose the demand, for the worst case scenario, which in this case is a failure of the single connection to the source.

Table 3. Percentage of nodes with corresponding ADF after the worst case failure scenario

Nr.	0-10%	11-20%	21-30%	31-40%	41-50%	51-60%	61-70%	71-80%	81-90%	91-100%
1727	100%									
3307	**2%**		**2%**	**2%**		8%	12%	14%	**16%**	**44%**
691	22%		4%	6%	8%	16%	10%	20%	2%	12%
757	6%	2%	4%	6%	6%	8%	10%	28%	16%	14%
353	24%	4%	2%	4%	12%	16%	18%	18%		2%
962	**4%**	**4%**	**2%**	**2%**	6%	10%	8%	14%	**22%**	**28%**

The two networks were further researched on the impact of the demand growth of 2% over 15 years, total 32%. As a consequence, the ADF_{avg} of the network 3307 would drop from 0.983 to 0.951, and in the case of 962 this would be from 0.976 to 0.927. In addition, the impact distribution shown in Table 3 would worsen because 3307 and 962 would have only 44 and 28% of the nodes losing less than 20% of their original demand in the scenario of the worst case failure, while 8 and 18% would have lost more than 60% of their original demand, respectively. In the final considerations, by analyzing the pipe hydraulic gradients, the networks were adjusted manually by enlarging a few diameters and eliminating the pipes not matching the template. Eventually, the network 3307 was selected as the final solution, having the ADF_{avg} of 0.993 and at the annual total cost slightly increased to 4.11 million. Figure 4 shows the layout of this network and the pressures ranging between 20.55 and 39.37 meters.

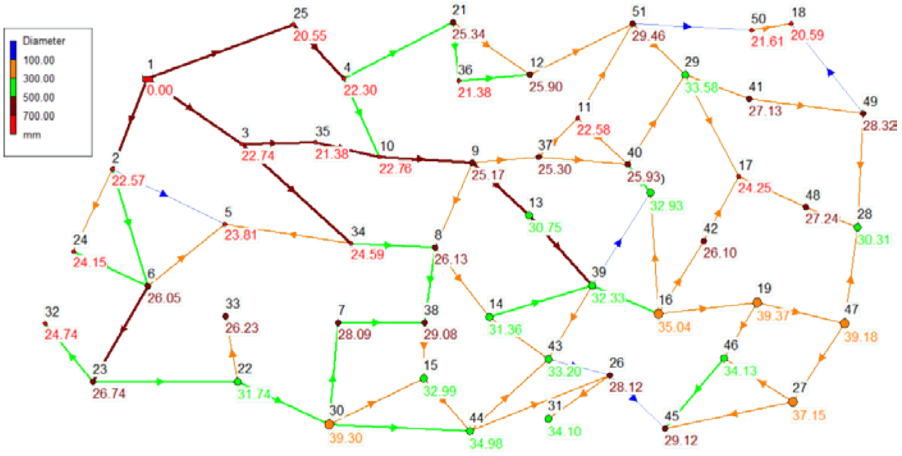

Figure 4. The pressures in the final layout 3307.

CONCLUSIONS

- NEDRA has proven to be pretty robust package that can process a very large sample of networks within relatively short period of time.
- The bottle-neck is in the network generation, mostly due to huge number of layouts to be generated to arrive at sufficient variety. Although a network design would rarely deal with thousands/hundreds of nodes/pipes, the number of combinations for a few dozen nodes can still be enormously high.
- The number of filtered layouts that fully comply with the template can be low beyond expectations. It may be therefore sensible to also filter the layouts that have a few connections not matching the template; these can be manually reconnected.
- The GA-optimiser managed to design the layouts of high resilience although 'geometrically' atypical for engineering practice. This somehow questions the need of a skeleton of secondary mains in the network and is to be researched further. GA certainly provides quick reference design for large number of layouts that can be manually adapted in the final stage.
- In the analysis of large number of layouts, the *ADF* proved to be a good measure of resilience, which can distinguish between the similar layouts. The network resilience, I_n, have shown less compliance with the loss of demand, by significantly lower values than the *ADF*, which does not reflect the resilience as high as it really appears to be.
- NEDRA can be used to efficiently analyse numerous alternatives and scenarios but needs much more rigorous testing before being integrated for wider use in practice.

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