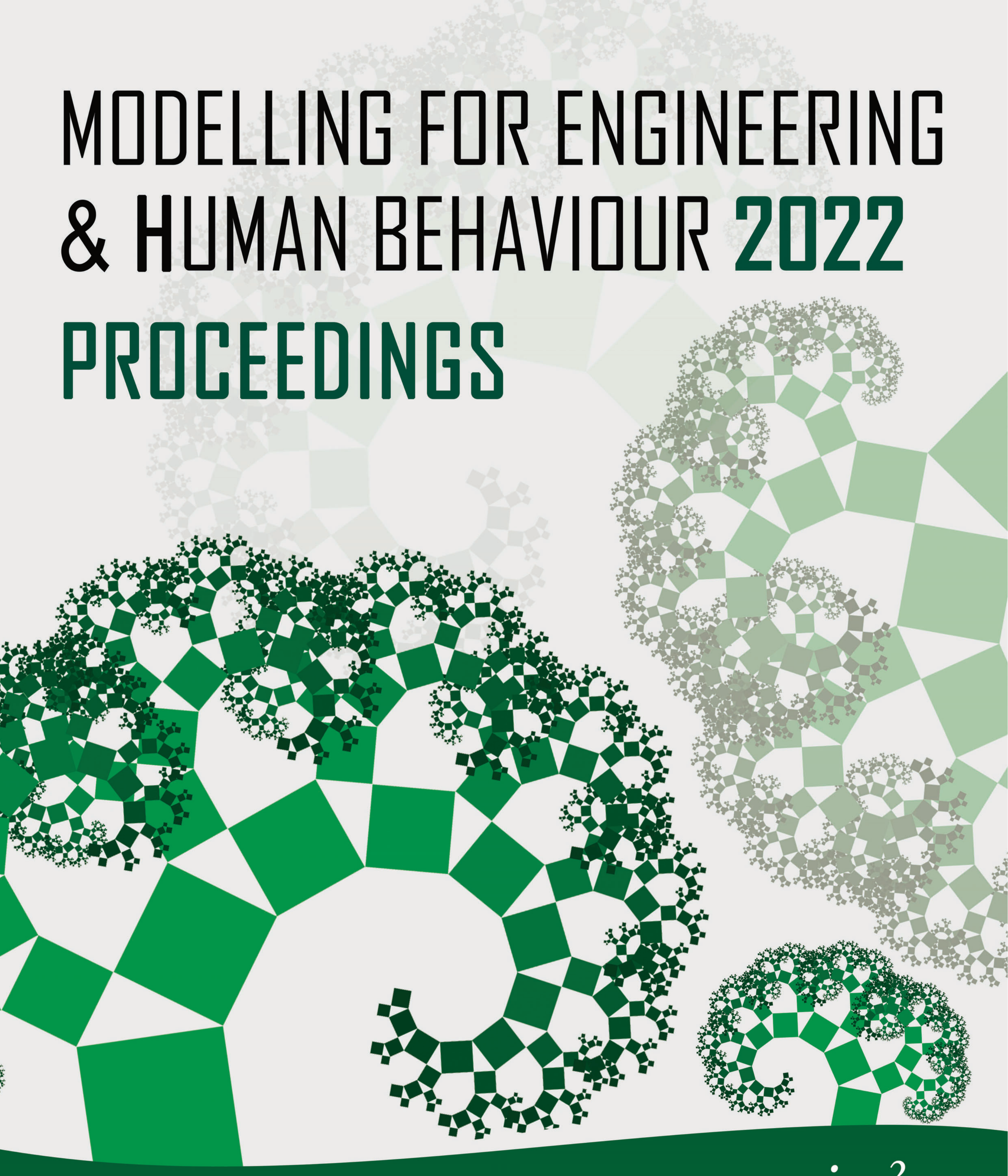

MODELLING FOR ENGINEERING & HUMAN BEHAVIOUR 2022

PROCEEDINGS

Edited by

Juan Ramón Torregrosa
Juan Carlos Cortés
Antonio Hervás
Antoni Vidal
Elena López-Navarro

im²
Instituto Universitario
de Matemática Multidisciplinar

UNIVERSITAT
POLITÈCNICA
DE VALÈNCIA

Modelling for Engineering & Human Behaviour 2022

València, July 14th-16th, 2022

This book includes the extended abstracts of papers presented at XXIV Edition of the Mathematical Modelling Conference Series at the Institute for Multidisciplinary Mathematics *Mathematical Modelling in Engineering & Human Behaviour*.

I.S.B.N.: 978-84-09-47037-2

November 30th, 2022
Report any problems with this document to imm@imm.upv.es.

Edited by: I.U. de Matemàtica Multidisciplinar, Universitat Politècnica de València.
J.R. Torregrosa, J-C. Cortés, A. Hervás, A. Vidal-Ferràndiz and E. López-Navarro

im^2
Instituto Universitario
de Matemática Multidisciplinar

24

Optimizing rehabilitation alternatives for large intermittent water distribution systems

Bruno Brentan[♭], Silvia Carpitella[♮], Ariele Zanfei[♯], Rui Gabriel Souza[♭], Andrea Menapace[♯],
Gustavo Meirelles[♭] and Joaquín Izquierdo[±]

(♭) Hydraulic and Water Resources Department, Federal University of Minas Gerais, Av.Presidente Antônio Carlos, Pampulha, Belo Horizonte, Brazil, brentan@ehr.ufmg.br, rui.g182@gmail.com, gustavo.meirelles@ehr.ufmg.br,
(♮) Department of Manufacturing Systems Engineering and Management, California State University, Northridge, CA 91330, United States, silvia.carpitella@csun.edu,
(♯) Faculty of Science and Technology, Free University of Bozen-Bolzano, Piazza Università 5, 39100, Bolzano, Italy; ariele.zanfei@natec.unibz.it, andrea.menapace@unibz.it,
(±) Institute for Multidisciplinary Mathematics, Universitat Politècnica de València, Cno. de Vera s/n, 46022 Valencia, Spain, jizquier@upv.es.

1 Introduction

Managing water distribution systems (WDS) in large metropolitan areas is a complex task. As highly connected, buried infrastructures, WDS are often exposed to failures and pose difficult control problems. To recover its capacity, various rehabilitation alternatives can be considered. Yet, specially in large, intermittent WDS, the wide spectrum of available alternatives leads to complex decision-making processes. To support WDS managers, hydraulic models can help disclose the impacts of interventions in the system. To cope with the inherent uncertainty, simulation processes built on top of those hydraulic models can shed light on each type of intervention. In-depth evaluations of the solutions under various criteria can help. Considering pipe replacement as a strategy for water network rehabilitation, we combine water distribution system analysis with multi-criteria analysis to rank alternatives for pipe replacement. Eight performance criteria are used to evaluate the rehabilitation alternatives. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [1] is adopted to rank the solutions. Our case study is the one proposed in the Battle of Intermittent Water Supply (BIWS) [2]. A budget constraint is set for alternatives' generation. Results show as pipe replacement is an important rehabilitation strategy, since the eight evaluation criteria are improved. Sensitivity analyses show the robustness of the best solutions, with just a few variations in ranking positions. The most frequent best solution is then hydraulically evaluated, showing the real benefits of pipe replacement in terms of pressure deficit reduction.

2 Methods

2.1 Leakage simulation

This work uses hydraulic theory to generate rehabilitation solutions. Simulations use Epanet 2.2 linked to Python using the library WNTR. Simulations are assessed by using TOPSIS. Leaks are distributed along the pipes to simulate leakage in a realistic way in WDS. We create a leaking node by splitting the corresponding pipe into two pipes connected by a node without demand but provided with an emitter that characterizes the leak. To avoid computational/mathematical problems derived from possible negative pressures, we create a new node which is linked to the leaking node by an artificial pipe, a short pipe of large diameter such to avoid additional headloss. A check valve to control the flow direction is added to this pipe.

2.2 Pipe replacement simulation

Pipe replacement is used by water companies to recover the hydraulic capacities of their WDS. After a pipe replacement, leaks are fixed, since the new pipe is fully watertight. A replaced pipe has same diameter and length as the old one, but its roughness is updated. this leak repair is simulated by setting the emitter coefficient of the leaking node to zero. Each pipe has a replacement cost, which is related to the price of the pipe itself and to the civil interventions as well. This cost limits the number of pipes to be replaced according to the budget of the water Company. In this work we follow the most recent references about cost as a function of diameter.

2.3 Evaluation Criteria

In addition to the costs, we use a set of indicators to evaluate the feasibility and advantages of a solution. Solutions are evaluated using eight multifaceted criteria (formulae omitted here).

I_1: percentage of hours that a consumer is served
I_2: proportion of consumers with continuous service
I_3: volume of water leakage
I_4: percentage of volume of water supplied to the users
I_5: pressure level at consumption nodes
I_6: percentage of users supplied continuously
I_7: average length of pipes under negative pressure
I_8: total energy consumed by pump stations

2.4 Multi-criteria and sensitivity analyses

Alternatives will be evaluated and ranked by using TOPSIS, which is able to deal with a huge number of alternatives, as it is the case of the present paper and can lead the evaluation by distinctively weighting the criteria, what allows sensitivity analyses (see, for example [3]).

3 Results

The developed methodology is applied to the BIWS network [CITA]. In this work only the pipe replacement solution is explored. This network has 2.859 junctions, 3.231 pipes, 7 pump, 6 reservoirs, 4 tanks, and 15 valves. Around 3600 leaks are set at a number of pipes. The final hydraulic model is then built with more than 10.000 nodes and 6.800 pipes. This makes hydraulic simulation harder than for the original setting and application of heuristic optimization is virtually impossible. Figure 1 presents the network topology depicting node elevation. A high elevation zone corresponds to the red nodes and a low elevation zone corresponds to the dark-blue nodes. Since the operational pressure is inversely proportional to the elevation, it is expected the high elevation zone to have supply problems derived from low pressures, while the low elevation zone will have problems with leaks due to high pressures.

A budget of €650.000 is considered, following the description of the Battle, and corresponds to the total amount of money that can be invested on rehabilitation. Considering this budget, 150

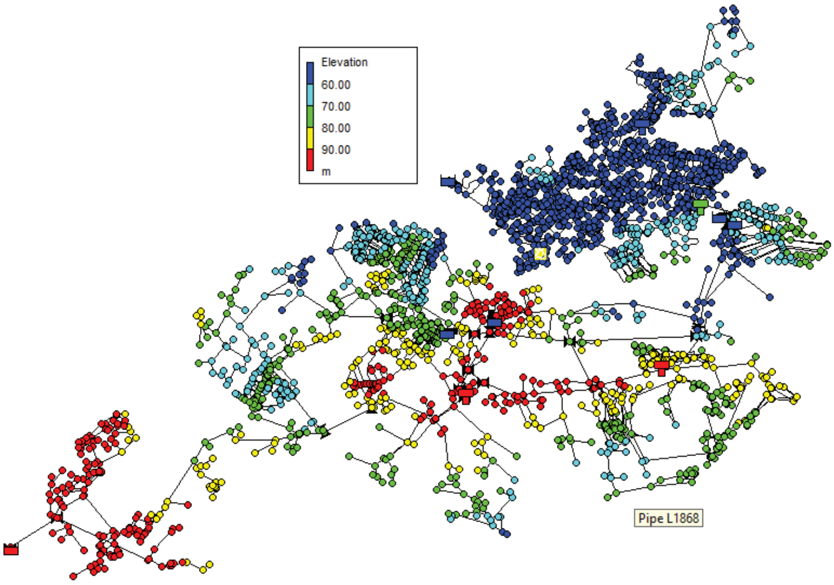

Figure 1: Water network topology of BWIS network highlighting the elevation of water system

solutions are simulated. Each solution is generated by randomly selecting pipes with leaking nodes to be replaced.

The solutions are evaluated based on the given indicators. Table 1 presents an statistical analysis of indicators. The box plot in Figure 2 analyzes the criteria value distribution. From Table 1 and the box plot in Figure 2 one verifies that some indicators do not vary significantly for pipe rehabilitation (e.g. I_1, I_4 and I_5). Comparing the statistical parameters and the criteria calculated for the original network, we note that I_1 is improved by all the solutions. However, a comparison among solutions shows slight differences between the minimum and maximum I_1 values. The same analysis can be explored for criterion I_4, which is improved by all the solutions, although, comparing minimum and maximum I_4 values, slight differences are noticed. Finally, the minimum of I_5 is virtually equal to the same indicator in the original network, while the maximum I_5 is slightly better than in the original network. The analysis on the other parameters shows that network rehabilitation by replacing pipes can improve indicators I_2, I_3, I_6, I_7 and I_8. More than that, observing the variation of these criteria, it is also possible to highlight that some solutions are better than others. It is also important to underline as some solutions can impair indicator I_6, and this is because reducing leaks in a certain region leads to higher pressures on this region but, since leaks depend on pressure, the remaining leaks can increase.

	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8
Average	0.957	0.908	0.432	0.923	0.769	0.848	59064	6731649
Std	0.0014	0.0343	0.0061	0.0009	0.0036	0.0881	33178	79017
Min	0.954	0.729	0.380	0.920	0.763	0.547	30163	6213527
Max	0.962	0.922	0.441	0.928	0.790	0.921	155425	7037708
Original	0.882	0.708	0.489	0.874	0.760	0.698	93091	6565165

Table 1: Statistical characterization of pipe replacement solutions and evaluation criteria calculated for the original network without any intervention

A question remains: which solution is more suitable to be applied considering that all them cost virtually the same? The MCDM method TOPSIS is applied to answer this question, specifically

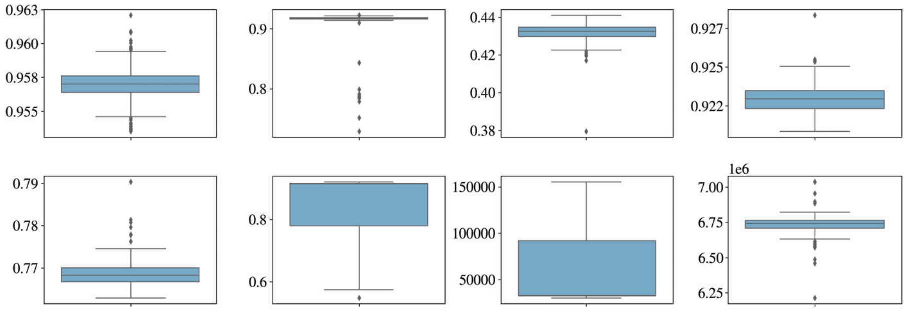

Figure 2: Box plot of each indicator used to evaluate the rehabilitation solutions

to rank the solutions based on evaluation criteria. Table 2 shows the five best solutions obtained by applying TOPSIS.

ID	TOPSIS Score	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8
22	0.975254	0.961	0.921	0.423	0.926	0.781	0.922	31464.0	6459619
128	0.971187	0.958	0.918	0.432	0.925	0.770	0.918	31778.0	6769291
115	0.970083	0.957	0.917	0.431	0.923	0.770	0.917	32191.0	6714131
141	0.96904	0.958	0.918	0.433	0.922	0.768	0.911	32227.0	6736640
18	0.968505	0.955	0.917	0.433	0.923	0.769	0.916	32709.0	6680980

Table 2: Ranking of five best solutions and the corresponding evaluation criteria

First, consider that criteria may have different weights. A robust methodology for ranking solutions must handle this situation. For this reason, a sensitivity analysis of criteria weight is conducted.

Finally, to evaluate the real impact of the solutions on the hydraulic system, the best solutions are hydraulically simulated. The results of this analysis can help decision makers to understand how and where the hydraulic features (e.g. flow and pressure) are changed.

4 Conclusions

Rehabilitation is paramount for water supply managers. The diversity of alternatives to improve hydraulic and energy performance involves complex decision-making. To help in the decision-making process, this work has presented a methodology for ranking pipe replacement solutions based on the TOPSIS methodology. Based on eight multifaceted criteria, solutions are evaluated and compared. To assess the robustness of the proposal, a sensitivity assessment has to be applied. It can be done with groups of criteria. Finally, the best solutions have to be hydraulically checked and the accompanying improvements made explicit.

References

[1] Chakraborty, S, TOPSIS and Modified TOPSIS: A comparative analysis *Decision Analytics Journal*, 2:100021, 2022.

[2] https://wdsa-ccwi2022.upv.es/battle-of-water-networks/

[3] Brentan, B.M. and Carpitella, S. and Izquierdo, J. and Luvizotto Jr, E. and Meirelles, G., District metered area design through multicriteria and multiobjective optimization *Mathematical methods in the applied sciences*, 45(6):3254–3271, 2022.