engineering proceedings

Proceeding Paper

Incorporating Flexibility in the Long-Term Design of Water Distribution Systems Using Operational Variables †

Dennis Zanutto [1,2,*], Andrea Castelletti [1] and Dragan Savic [2,3]

1 Dipartimento di Elettronica Informazione e Bioingegneria, Politecnico di Milano, 20133 Milano, Italy; andrea.castelletti@polimi.it
2 KWR Water Research Institute, 3430 BB Nieuwegein, The Netherlands; dragan.savic@kwrwater.nl
3 Centre for Water Systems, University of Exeter, Exeter EX4 4QF, UK
* Correspondence: dennis.zanutto@polimi.it
† Presented at the 3rd International Joint Conference on Water Distribution Systems Analysis & Computing and Control for the Water Industry (WDSA/CCWI 2024), Ferrara, Italy, 1–4 July 2024.

Abstract: This work investigates the effect of operational variables on water distribution system design optimisation. The "Anytown" problem is approached with three formulations of the operational decision variables to examine how different models of such components affect the design solutions and the optimisation process. The formulations that jointly optimise operations and design decision variables can double the energy surplus for the same cost compared to a design-only formulation.

Keywords: distribution; design; optimisation; operations; flexibility

Citation: Zanutto, D.; Castelletti, A.; Savic, D. Incorporating Flexibility in the Long-Term Design of Water Distribution Systems Using Operational Variables. *Eng. Proc.* **2024**, *69*, 46. https://doi.org/10.3390/engproc2024069046

Academic Editors: Stefano Alvisi, Marco Franchini, Valentina Marsili and Filippo Mazzoni

Published: 4 September 2024

1. Introduction

Designing water distribution systems (WDSs) is a complex challenge that involves non-linear relationships, multiple objectives, and a mixed integer decision space. Additionally, WDSs have over a century's lifespan, making them highly susceptible to long-term uncertainties. Multiple approaches have been proposed in the literature to navigate these (deep) uncertainties, such as robust [1], staged [2], flexible [3], and adaptive design [4]. Yet these approaches predominantly focus on planning and the design variables (e.g., pipe siting and sizing), often overlooking the significant impact that operations can have on the design solutions and their performance over the lifespan.

Adjustments in operational variables, such as pump scheduling and valve status settings, offer a flexible response to uncertainties. These variables can be modified with greater frequency and at a lower cost than network infrastructure interventions. However, from a design perspective, the actual values of these decision variables (DVs) appear as an additional source of uncertainty as they depend on the future realisation of the other uncertainties still unknown at the design phase.

In this work, we explore the relationships between the design and operational variables in optimising WDS design. The same WDS rehabilitation problem is approached with multiple formulations as follows: (1) a pure design optimisation problem with fixed operations, (2) an integrated design and operations optimisation, and (3) a two-stage independent design and operations optimisation. Thus, we give some preliminary insight into the following questions: What is the best way of formulating a WDS joint design and operations optimisation problem? What is the impact of operations on the design solution?

2. Case Study

The "Anytown" network problem [5] seeks to determine the least cost design to rehabilitate the existing infrastructure of a town to meet projected water demands. The possible design interventions are pipe cleaning and duplication for the existing network section, mandatory pipe installation between new nodes, and installing up to two additional tanks. The operational decision variables are the pumps' operational schedules at the water source. The first objective is the solution's total cost, which must consider pumping and capital expenditures. The second objective is Todini's Reliability Index [6]. The system is also subject to minimum pressure constraints.

A full description of the problem can be found in [3,5]. Compared to other studies, in this analysis, the only loading condition considered is the 24 h simulation under the average demand pattern, as the additional fire flow conditions are expected to influence the design but not the operational variables, which are fixed during these scenarios.

3. Methodology

We implement three different formulations of the operational decision variables for the selected optimisation problem (see Section 2). The aim is to investigate their effect on the solutions and to gather additional insight into the behaviour of the optimisation process. The first formulation is a classic rehabilitation problem, where the design variables are optimised and the operational ones are fixed a priori. We will refer to this as the "pure design" formulation. In the second formulation, operations and design are optimised simultaneously thus considerably increasing the search space ("integrated"). Finally, we test a "two-phase looped" approach that optimises design and operational variables separately. In the "outer loop", the optimisation algorithm only deals with the design variables. The solutions are then fed to the "inner loop", where a second instance of the same algorithm considers the operations and estimates the total cost (capital and pumping expenditures). The design solutions are then evaluated and modified based on their operationally optimised version resulting from the inner loop.

4. Experimental Settings

We selected a classic setup of the literature to run the experiments: the Evolutionary Algorithm NSGA-II explores the solutions space and EPANET 2.2 solves the network hydraulics equations to estimate the fitness function. Each optimisation is run for 30,000 generations (convergence at 5000), 16 seeds, and a population of 100 individuals. Hydraulic simulations are run with an hourly time step.

The design decision variables are coded into strings for all the optimisation problem formulations as follows: (1–6) selected diameter for the new pipes; (7–76) couple "taken action" (do nothing, clean or duplicate) and diameter for the already existing pipes; (77–80) location and volume for two tanks. The operational decision variables (81–104) representation is a single 24-value string with the number of active pumps at each hour.

5. Results and Discussion

The outcomes of the multi-objective optimisation comparing the three distinct formulations introduced in Section 3 are represented in Figure 1a. Results show that the "integrated" and "two-phase" approaches, which optimise both design and operational DVs, significantly outperform the "pure design" strategy. Specifically, for solutions with a cost of around 10 million dollars, the "integrated" approach enhances the Reliability Index by 150% over the traditional "pure design". At the same time, the "two-phase" method achieves a 100% improvement. Similarly, at higher cost levels ($15 million), they offer 60% and 50% enhancements in reliability, respectively.

The "pure design" formulation is optimised with three different pump scheduling decided a priori (Figure 1b). Still, all the evaluated settings are less performant than the joint design and operations approaches. Specifically, the first test employs an optimised pumping schedule reported in the literature [7] that runs two pumps all day and the third one only during peak hours (between 9 and 18 h). This setup achieves a performance very close to running all three pumps all day (second test). A higher pump usage does not improve the network's performance enough to explain the distance between the Pareto fronts. The superior performance of these solutions can be attributed to the more sophisticated operational scheduling of the pumps. Indeed, the median pump pattern rarely runs pumps constantly throughout the day or all three simultaneously, but it tends to operate two, mostly during the night, with an on–off behaviour. Thus, this suggests that the EA can exploit Todini's metric, producing an unrealistic solution for real-world applications due to undesired frequent pump switching.

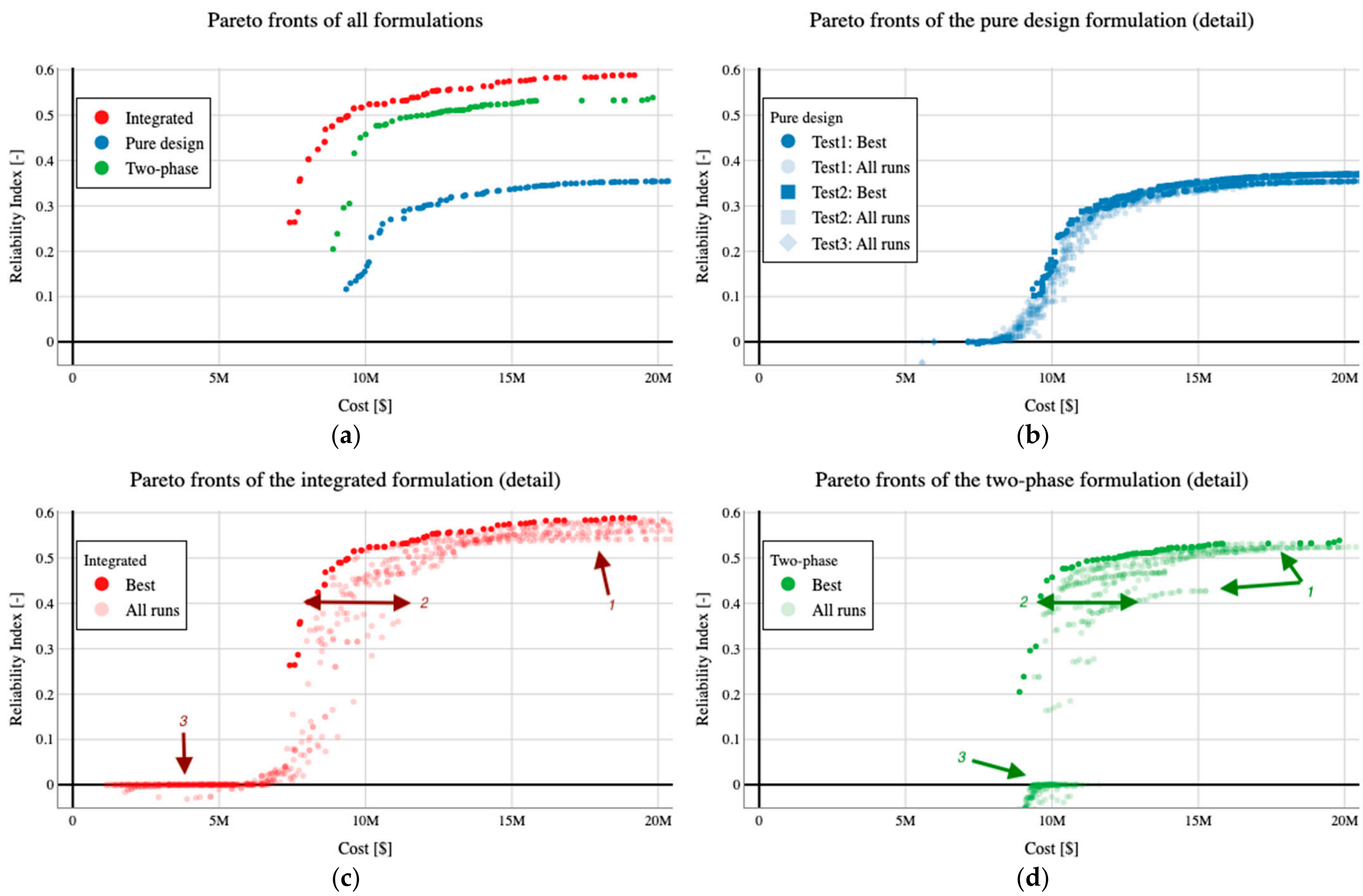

Figure 1. (**a**) Best Pareto front of the three formulations; (**b**–**d**) details of the individual fronts. Arrows are explained in the text.

The third test of the "pure design" formulation employs this peculiar pattern extracted from the "integrated" approach, but it does not converge. While optimising the operations for a given design is natural, attempting to reverse this process by tailoring the design optimisation to specific operational settings requires careful consideration.

Comparing the two formulations that optimise operations and design, the "integrated" approach has the edge over the "two-phase". Figure 1c,d show each formulation's PF for all the randomly initiated optimisation runs. These formulations have bigger search spaces and, consequently, more local optima (see arrows 1 and 2). One particularly strong local optimum of infeasible solutions emerges (arrow 3) but of a different nature for the two formulations. With the "integrated" formulation, around 30% of the randomly initialised populations end up there and have all the final solutions with near-null pump usage. Without adequate pumping, feasible and infeasible design solutions become hard to distinguish. With the "two-phase looped" approach, the cluster indicated by arrow 3 appears because a small number of infeasible but cheap designs survive in every run.

6. Conclusions

This study illustrates the critical role of the operational variables in optimising water distribution system design and how their formulation influences the outcome of the optimisation process. Through the "Anytown" case study, we explored the following three different formulations of the operational decision variables in a common rehabilitation problem: "pure design" optimisation with fixed operations, "integrated" design and operations optimisation, and a "two-phase looped" design and operations optimisation.

The formulations that consider both design and operations are more efficient than the "pure design" and provide a higher energy surplus (Todini's Reliability Index) for the same cost. When the design problem is approached with fixed operations, the settings assigned influence the outcome of the classic design optimisation problem.

This preliminary study has some limitations, such as using Todini's Reliability Index as the second objective—promoting the "erratic but efficient" behaviour of the controllable elements—and the simplistic assumptions on the loading conditions and constraints. In future work, we will focus on providing a more detailed explanation of the effect of the operations on the system properties and refining the two-phase looped approach.

Author Contributions: Conceptualisation, methodology, D.Z., A.C. and D.S.; software, D.Z.; validation, formal analysis; investigation; resources; data curation; writing—original draft preparation; writing—review and editing; visualisation, D.Z., A.C. and D.S.; supervision, A.C. and D.S.; project administration; funding acquisition, D.S. All authors have read and agreed to the published version of the manuscript.

Funding: This project has received funding from the European Research Council (ERC) under the ERC Synergy Grant Water-Futures (Grant agreement No. 951424).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The code and results are available on GitHub and Zenodo [8,9].

Acknowledgments: We thank Lydia Vamvakeridou-Lyroudia and Mark Morley for their support.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Jung, D.; Lee, S.; Kim, J.H. Robustness and Water Distribution System: State-of-the-Art Review. *Water* **2019**, *11*, 974. [CrossRef]
2. Creaco, E.; Franchini, M.; Walski, T.M. Taking Account of Uncertainty in Demand Growth When Phasing the Construction of a Water Distribution Network. *J. Water Resour. Plan. Manag.* **2015**, *141*, 04014049. [CrossRef]
3. Basupi, I.; Kapelan, Z. Flexible Water Distribution System Design under Future Demand Uncertainty. *J. Water Resour. Plan. Manag.* **2015**, *141*, 04014067. [CrossRef]
4. Cunha, M.; Marques, J.; Creaco, E.; Savic, D. A Dynamic Adaptive Approach for Water Distribution Network Design. *J. Water Resour. Plan. Manag.* **2019**, *145*, 04019026. [CrossRef]
5. Walski, T.M.; Brill, E.D.; Gessler, J.; Goulter, I.C.; Jeppson, R.M.; Lansey, K.; Lee, H.-L.; Liebman, J.C.; Mays, L.; Morgan, D.R.; et al. Battle of the Network Models: Epilogue. *J. Water Resour. Plan. Manag.* **1987**, *113*, 191–203. [CrossRef]
6. Todini, E. Looped Water Distribution Networks Design Using a Resilience Index Based Heuristic Approach. *Urban Water* **2000**, *2*, 115–122. [CrossRef]
7. Siew, C.; Tanyimboh, T.T.; Seyoum, A.G. Penalty-Free Multi-Objective Evolutionary Approach to Optimization of Anytown Water Distribution Network. *Water Resour. Manag.* **2016**, *30*, 3671–3688. [CrossRef]
8. Zanutto, D. *Zannads/BevarMejo: 24.04.0 Release*, Version v24.04.0; Zenodo: Geneva, Switzerland, 2024. [CrossRef]
9. Zanutto, D. *BeMe-Lab*, Version v22.10.0; Zenodo: Geneva, Switzerland, 2022. [CrossRef]