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Performance and Operational Transformation for Effective Water Network Management †

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Abstract: In the management of drinking water networks, operational costs generally play second fiddle to capital investment costs, because their optimization strategies are often distinct. However, under the pressure of an aged network infrastructure with limited available budgets, a solution that targets the optimization of capital expenditure (CAPEX) and operational expenditure (OPEX) is desirable for reducing water losses and achieving lower non-revenue water (NRW). As part of a strategy to minimize pipe bursts and physical losses, Suez and Optimatics, a Suez software company, have partnered to develop an integrated approach. The result is a framework that allows Suez operators to identify strategies for pipe renewal and pressure management that minimize OPEX and CAPEX and exploit positive interactions between them, without degrading water network performance.

Keywords: asset management; pressure management; water distribution network optimization; NRW; physical water losses reduction; burst reduction

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1. Introduction

For municipalities, the protection of public health, which entails providing safe water for all consumers, is a key driver for any urban strategy. The maintenance of water networks and the optimization of their operation—including sustained reductions in physical water losses and sustained minimization of network supply interruptions—are imperative.

However, network infrastructures are ageing, and in the face of urban densification and expansion, water network management is an expensive and time-consuming endeavor, as it is increasingly difficult to provide acceptable levels of water distribution services while respecting the budgetary constraints to which utilities are subjected. Therefore, optimizing the chain of actions for the management of water distribution systems represents a major economic opportunity for operators to achieve a sustainable level of performance, particularly when the water resource is limited.

Consequently, an integrated approach must build a bridge between a long-term investment strategy that aims to improve resilience and support growth and a network's daily operating strategy that is focused on minimizing operational expenditure (OPEX) while maximizing the system's levels of service

This paper presents an approach developed by Suez and Optimatics, a Suez software company, that has been used to develop strategies to reduce OPEX while simultaneously improving the service levels and reducing water losses for several water networks.

2. Materials and Methods

As prescribed in the time-weighted average (IWA: International Water Association) methodology [1], pipe renewal and pressure management are two strategies that help to reduce the operational costs related to physical losses and bursts in the system.

Once these potential actions are identified, the challenge is to make informed decisions on how and where they need to be applied. This entails questions on how and where to replace or rehabilitate pipes and manage network pressure. The estimation of the impacts of these actions is a challenge due to their interrelationships. In addition, factoring in these interactions induces an exponentially more complex decision-making process that needs to be handled efficiently.

To address these questions, Suez and Optimatics developed the three-step framework illustrated in Figure 1.

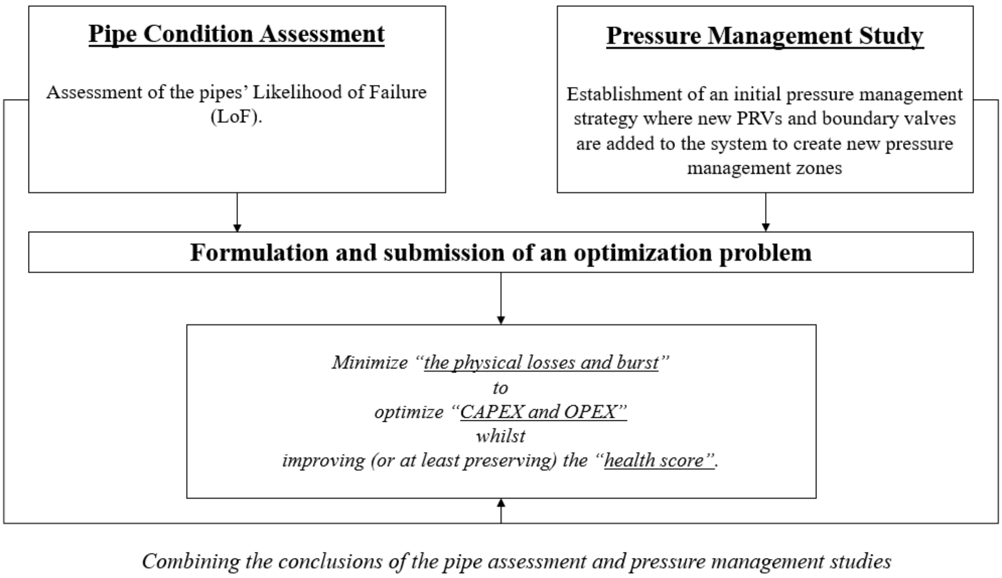


Figure 1. Framework of the optimized burst reduction methodology.

2.1. Pipe Condition Assessment

An assessment of pipe condition is derived using Netscan^{TM}, an in-house Suez solution that undertakes analysis based on compiling in-depth information on infrastructure, environmental, and operational conditions (a pipe's age, material, and diameter; soil characteristics; road traffic; pressure; bursts history, etc). A machine learning algorithm, based on random forest and subject to IP protection by Suez, was utilized to generate a forecasting model. The pipe condition assessment model establishes the link between the identified influential factors and the historic failure of the pipes. The description of this algorithm (which is not the main focus of this paper) is available in [2].

Within this framework, pipe condition-based assessment can also be realized; this activity contributes to the robustness of the failure-forecasting model. The solution produced from the pipe-condition assessment model generates the inspection plan by selecting the most representative pipes via clustering for field inspections, and then extending these results to the entire network for a more comprehensive physical diagnosis.

In our studies, this solution allows for the prediction of the likelihood of failure for each pipe of an entire network.

2.2. Pressure Management Study

Using a PICCOLO or EPANET hydraulic model [3], the pressure management study identifies the areas of a network where the pressure can be reduced without impacting the level of service, while complying with regulatory fire-flow constraints. The difference between the pressure at critical point(s) in different conditions of supply (including fire flow) is evaluated and compared with a minimal acceptable pressure defined by the user (a threshold value of 2 bars is generally considered). For each of these areas, the placement of the pressure reducing valves (PRVs) and the boundaries valves are defined, as well as the pressure settings.

2.3. Optimization Problem Formulation and Resolution

For water systems analysis, one could be assured of finding the global optimum solution to a problem only if the problem were small enough to allow every possible solution to be evaluated, i.e., complete enumeration. Real-world water problems are rarely small, and the size of the total solution space is generally exponential with respect to the number of decision-variables candidate solutions.

To overcome this issue, the optimization problem was formulated and solved using Optimizer™ (Optimizer version 5.3.2, manufactured by Optimatics, Adelaïde, Australia), a multi-objective optimization software platform developed by Optimatics and adapted for hydraulic systems. Optimizer™ employs computational intelligence (CI) by deploying an ensemble of different global optimization algorithms to solve complex water engineering problems and considers different alternatives to help generate plans with the highest-discovered performance with respect to the set of objectives defined in the formulation, as shown in Figure 2.

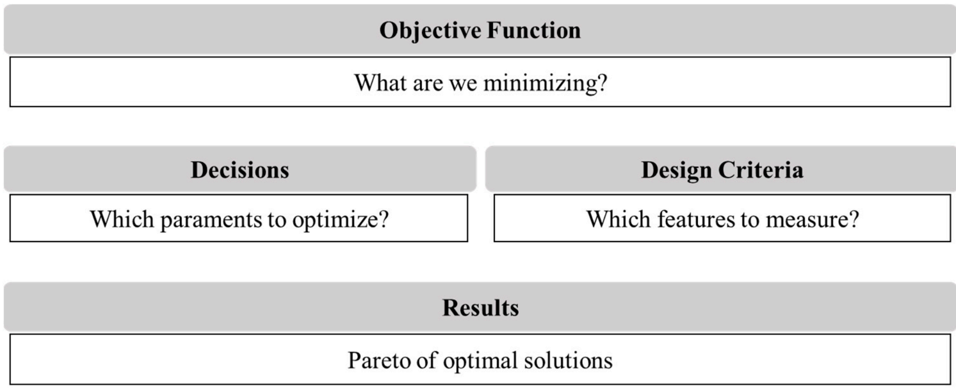


Figure 2. Optimized problem formulation.

In our approach, the objectives were defined as follows:

- CAPEX: pipe replacement investment plus pressure management investment;
- OPEX: marginal cost of the water lost in the distribution network plus repair cost for the bursts;
- Network health score: the combined indicator that is a score estimated by combining the age of each pipe, their likelihood of failure, and the new operational pressure.

The criteria used to evaluate the performance of the plans are the reduction of the physical losses and the maintenance of a minimal pressure for every node in the network.

The formulation of the optimization problem considers thousands of decisions (5000 to 20,000 decisions in our networks) on pipe replacement (from the pipe condition assessment), installation of new PRVs and boundary valves to define new pressure zones, and the settings of the existing and new PRVs (from the pressure management study). The impacts of the decisions on the performance criteria are the following:

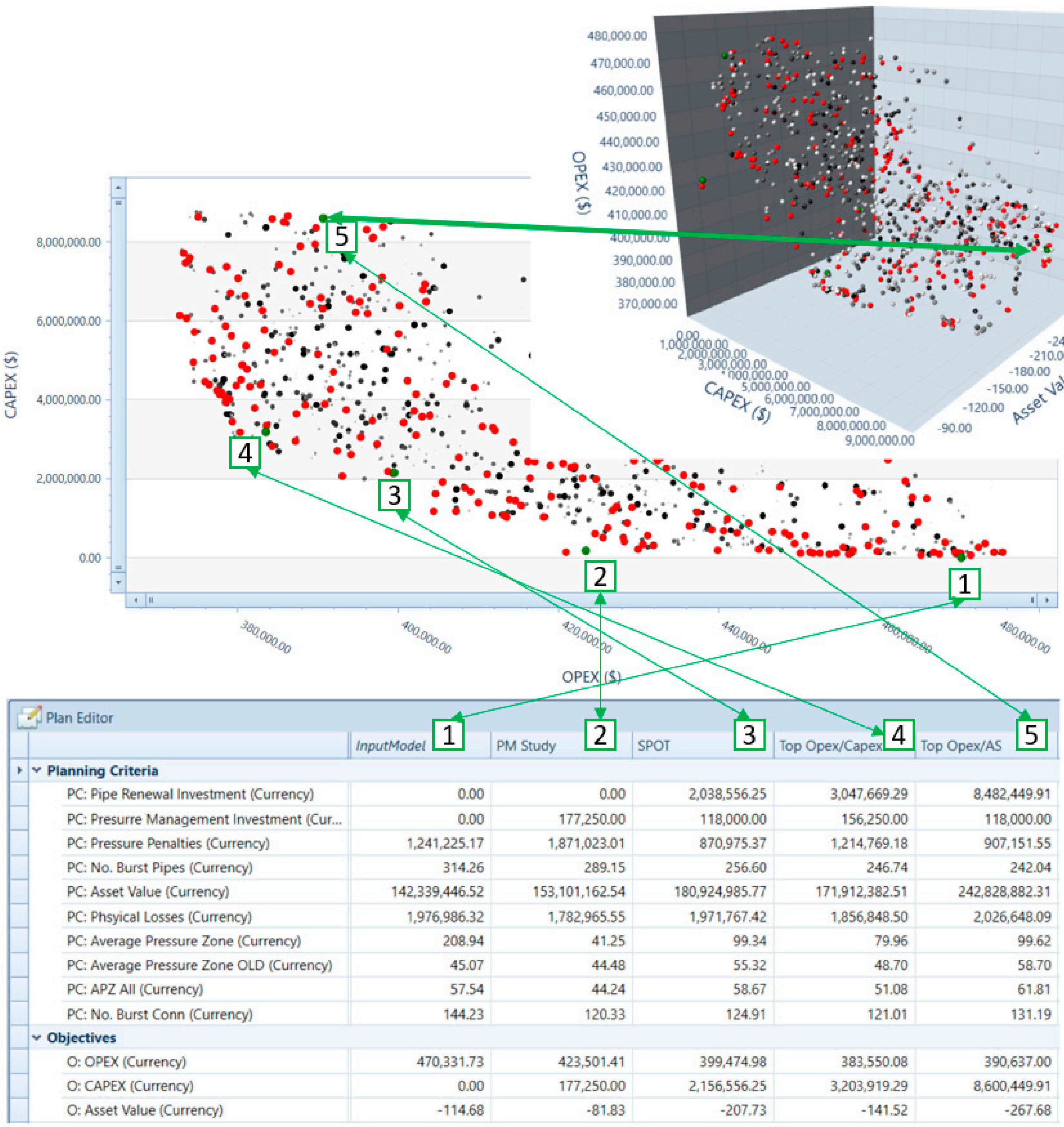
- The replacement of a pipe removes the physical losses related to this pipe and resets the likelihood of failure for this section of the network to 0.
- The reduction of the pressure reduces the leakage rate of the pipes in the area but can cause a violation of the pressure constraint for the nodes in the same area.
- The replacement of a pipe and the reduction of the pressure increases the health score of the network

The resolution of this optimization problem aims to find the best configuration of the PICCOLO or EPANET hydraulic model to minimize the CAPEX and the OPEX, and to improve the health of the network; this is a multi-objective problem. Despite the literature outlining the extensive research undertaken on water network optimization [4], most studies limited the number of objectives to one or, at most, two. There is little literature with a higher number of objectives [4].

Optimizer^{TM} algorithms use an ensemble of carefully adapted genetic algorithms to solve this problem. Optimizer deploys an ensemble algorithm to cost out and hydraulically evaluate the suitability of hundreds of thousands of trial solutions to narrow in on a range of viable, near optimal, solution alternatives for each problem objective. The global search algorithm used by Optimizer is highly adaptable and configurable. The algorithm applies different search strategies for single and multi-objective problems. For multi-objective problems, Optimizer uses a variant of NSGA-II (non dominated sorting genetic algorithm II, which is a fast sorting multi-objective algorithm) [5] with some changes to default parameters and operators. This algorithm keeps a steady-state population and uses specialized adaptive mutation operators to make local improvements to this population. Optimizer's search runs hydraulic models for each candidate configuration, to generate a set of optimal solutions in a Pareto front. Each solution is a plan depicting a set of replaced pipes and new PRV and pressure settings. Each of the best candidate plans are represented by a point in the Pareto front.

Figure 3 displays five plans (in green) that provide a good OPEX benefit (similar x values) with different network health scores (the CAPEX objective is halved between the plans), illustrating how there are different ways to improve the operation. A deeper, and more detailed examination indicates, within the Pareto front, the best trade-off to improve the OPEX as well as the state of the assets.

Based on these results, the final strategy is then established after a discussion with the different stakeholders of the water system.



	InputModel	PM Study	SPOT	Top Opex/Capex	Top Opex/AS
Planning Criteria					
PC: Pipe Renewal Investment (Currency)	0.00	0.00	2,038,556.25	3,047,669.29	8,482,449.91
PC: Presurre Management Investment (Cur...	0.00	177,250.00	118,000.00	156,250.00	118,000.00
PC: Pressure Penalties (Currency)	1,241,225.17	1,871,023.01	870,975.37	1,214,769.18	907,151.55
PC: No. Burst Pipes (Currency)	314.26	289.15	256.60	246.74	242.04
PC: Asset Value (Currency)	142,339,446.52	153,101,162.54	180,924,985.77	171,912,382.51	242,828,882.31
PC: Phsyical Losses (Currency)	1,976,986.32	1,782,965.55	1,971,767.42	1,856,848.50	2,026,648.09
PC: Average Pressure Zone (Currency)	208.94	41.25	99.34	79.96	99.62
PC: Average Pressure Zone OLD (Currency)	45.07	44.48	55.32	48.70	58.70
PC: APZ All (Currency)	57.54	44.24	58.67	51.08	61.81
PC: No. Burst Conn (Currency)	144.23	120.33	124.91	121.01	131.19
Objectives					
O: OPEX (Currency)	470,331.73	423,501.41	399,474.98	383,550.08	390,637.00
O: CAPEX (Currency)	0.00	177,250.00	2,156,556.25	3,203,919.29	8,600,449.91
O: Asset Value (Currency)	-114.68	-81.83	-207.73	-141.52	-267.68

Figure 3. Illustration of three plans/solutions allowing OPEX benefit with different net.

3. Results and Discussion

This approach has been implemented on distribution systems operated by Suez in France and other countries. The five first-implemented studies achieved promising results (network model characteristics in Table 1). The action plan from the Network 5 has already been engaged, based on the optimal plan, suggested by optimization by the network operator and the municipality. All PRVs have been installed. The effect of the action plan will be followed up and feedback will be shared.

Table 1. Network model components.

	Junctions	Reservoirs	Tanks	Pipes	Pumps	Valves
Network 1	22,545	26	64	23,488	50	581
Network 2	22,220	8	13	23,268	13	264
Network 3	6435	3	0	7572	0	521
Network 4	5011	12	5	5149	7	42
Network 5	13,709	45	146	14,539	18	238

As shown in the Table 2, the studied five networks represent different situations in terms of network size, age, leak rate, and NRW.

Table 2. Network features and performance.

	Current Situation					Target		Optimization Parameters	Results
Case	Length (km)	Network Average Age (years)	Leak Rate (nr/annual)	Physical Water Losses (m^3)	NRW (%)	NRW to Be Achieved	Volume to be Gained (m^3)	Number of Decisions	Number of Bursts
Network 1	853	40	0.17	1,200,492	24%	19%	972,431	23,488	24.1
Network 2	915	45	0.42	1,612,139	17%	13%	853,997	23,268	66
Network 3	480	35	0.79	4,576,927	45%	N/A [1]	N/A	7572	49.9
Network 4	670	55	0.24	584,669	28%	22%	198,700	5149	30.8
Network 5	1859	42	0.17	1,871,589	31%	22%	1,042,860	14,539	67.5

Note: [1] Network 3 is a DMA of a bigger network with the following performance targets: NRW: 37.4%; Water loss reduction: 1.964.969 m^3.

As shown in Table 3, this method was customized to meet the requirements of the operator and the utility of each studied network. For case 4, the utility looked for optimizations to help them make decisions about pressure management projects, because of the important investment required. For case 5, the renewal plan was constrained by the annual budget, but not by the annual length.

Table 3. Optimization and results.

	Actions to Be Optimized	Reduction of OPEX (%)	Reduction of Physical Water Losses (m^3)	Network Health Score
Network 1	Renewal: 0.5–1%/a Pressure management with maximum 10 PRVs	16.8%	187,018	Increase 27%
Network 2	Renewal: 0.5–1%/a. Pressure management with maximum 18 PRVs	17.0%	239,039	Increase 1.4%
Network 3	Renewal budget: 500 k€/a. Pressure management with maximum 6 PRVs	12.7%	761,902	Increase 22%
Network 4	No renewal plan taken (asked by operator) Pressure management with maximum 31 PRVs	20.2%	113,000	Increase 24%
Network 5	Renewal: 0.5–1%/a. Pressure management with maximum 17 PRVs	18%	120,137	Increase 23.7%

The results show a reduction of between 12% to 20% in OPEX, while improving the overall water service by reducing network supply interruptions and water losses and enhancing the health of the network asset.

The optimization results contribute to the NRW reduction strategy. Figure 4 (blue line) shows for Network 5 the evolution over time of NRW from the implementation of the optimization results (renewal plan and pressure management) and other actions, such as leakage detection and meter renewal. Due to the optimization, the utility achieved good balance between the available budget and performance. The sum of the OPEX reduction and water saving (100,000 €/year) was equal to the additional CAPEX (100,000 €/year); i.e., it took only one year for the return of the investment.

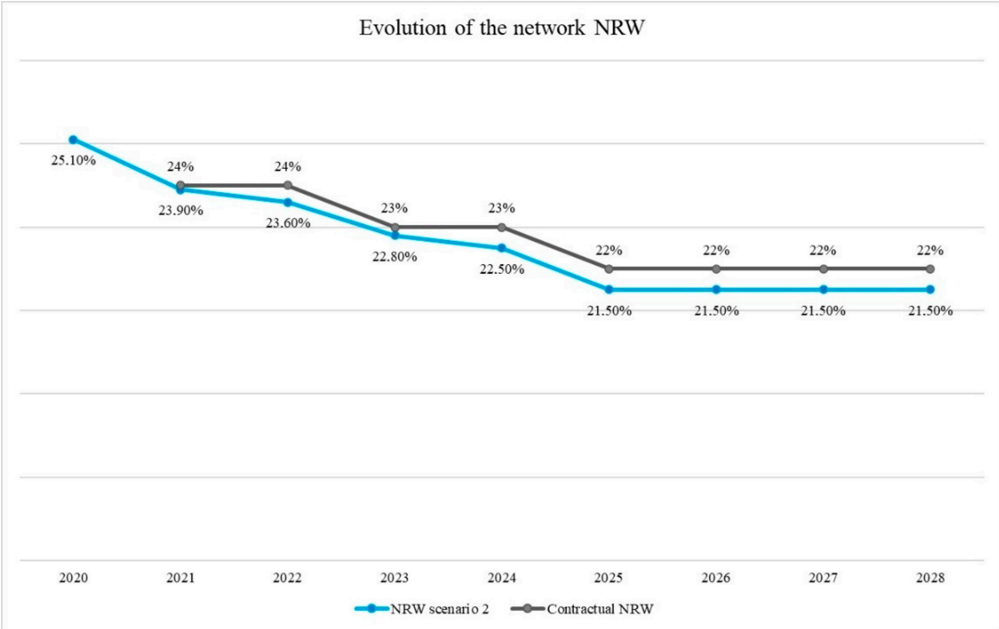


Figure 4. Evolution of NRW of Network 5 with the optimized action plan.

4. Conclusions

Distribution network water loss problems are interlinked. Solving one issue may lead to other types of problems. Due to the aging infrastructure and investment constraints, we searched for solutions that provide a balance among capital expenditure (CAPEX), operational expenditure (OPEX), and performance. The approach developed by the Suez Ventures company (Suez) and Optimatics, a Suez software company, and its application on several networks have shown that it is possible to propose adequate responses to improve network performance without violating operational or regulatory constraints, through an optimized implementation of multiple solutions at the same time within the framework of a comprehensive formulation.

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