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Systematic Method of Retrofitting Wastewater Transportation Systems for Enhanced Reliability

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While the treatment of wastewater is an important issue that received significant attention in the past decades, improving the related technologies is only one part of a more complex task. Domestic wastewater is usually transported via the city's sewer system, and in many places, it is combined with rainwater. This means that disturbances, such as heavy rainfall or failures in the pipeline system, can lead to floods of polluted wastewater. Thus, it is important to design such transportation systems to be reliable. This work presents a methodology for generating several potential extensions to retrofit an existing water transportation network and increase its reliability. Reliability and feasibility evaluation is performed via the P-graph framework, after which the non-dominated networks are collected. Results of the presented case study show that reliability can be increased 3 times by adding only some of the possible extensions to the network. The methodology proposed analysed 512 plausible retrofitting alternatives, from which 20 are non-dominated networks. This range of alternatives provides designers with insightful information to decrease water pollution and the vulnerability of wastewater systems.

1. Introduction

Preserving water is a priority task that humankind must address to ensure the sustainability of the various species on the planet. Consequently, various organisations have emphasised the need to mitigate issues such as ocean acidification, plastic pollution, and freshwater scarcity. The United Nations Organization (UN), for instance, has defined two sustainable development goals (SDG) related to water access and conservation, i.e., ensuring the availability and sustainable management of water and the conservation of oceans and marine resources (United Nations, 2015).

Wastewater treatment has been considered as a natural alternative to cope with the problems related to water quality and availability. However, the fast population growth has resulted in increased water pollution. Currently, more than 380,000,000,000 m^3/y are produced across the world, and this quantity is expected to increase by 24 % by 2030 (Qadir et al., 2020). The increase in wastewater has caused the capacity of transport and treatment systems to be exceeded, especially during rainy seasons when the volume of water to be treated may be significantly enlarged.

The existence of wastewater systems susceptible to disturbances, e.g., heavy rains, aggravates the problem as it can result in the release of a large volume of untreated wastewater. In combined sewer systems, for instance, rain runoff is mixed with domestic and industrial wastewater, and the mixture is discharged with no treatment into waterbodies in case of overflows, resulting in significant water pollution and health concerns (US EPA, 2023). Naturally, failures in the system's components constitute a serious set of disturbances, as pump malfunctions or pipe breakdowns can render the treatment systems partially or totally inoperative. To enhance the contribution of wastewater treatment systems to water sustainability, they should be designed considering criteria that evaluate their behaviour in the face of disturbances and failures. In the case of existing wastewater treatment systems, these could be retrofitted to increase their operation capacity and improve properties such as their robustness, resilience, and reliability.

Reliability of a system generally describes the probability that the system is capable of carrying out an acceptable operation, considering the potential disruptions of its components. In the case of a processing

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system, it is the probability that the products can be generated in the required amount with the required quality. The reliability of a transportation system can refer to the probability that a given expected amount of material or energy reaches its destination. Determining the reliability of a system requires the estimation of the reliabilities of its individual components (Barlow and Hunter, 1961). Then, the reliability of the system is a result of some formula, calculation, or simulation (Henley and Gandhi, 1975).

The methods to determine system reliability can be split into two major categories: deterministic and stochastic. Deterministic methods generate an exact result, assuming that the component reliabilities are correct. For simpler systems, such as series-parallel structures, closed formulas exist (Birolini, 2017), while systems with more complex structures require specialised methods (Goel et al., 2002). Stochastic approaches are often applied to systems with complex non-linear models, where deterministic calculation is either not applicable or too complicated (Abubakar et al., 2015). These methods can estimate the reliability of any system; however, their result is just that: an estimation instead of the actual analytical result, and the sharpness of the estimation depends on how the method is tailored to the specific problem.

Basic transportation networks have a simple structure where any route from the source to the target is an operational transport route. With multiple sources and targets, each with its own requirements, a single route is not sufficient. Instead, a mathematical model can describe the functionality. A water transportation system in a city even has flow restrictions since the pipes have limited throughput capabilities.

Karimian et al. (2015) applied Evolutionary Polynomial Regression to estimate the failure rates of pipeline segments based on historical data and the properties of the pipeline. Alsharqawi et al. (2020) combined this technique with fault-tree analysis to estimate the reliability of water distribution networks. Paez and Filion (2020) differentiated the water distribution system reliability based on the cause (e.g., pipe breaks or load fluctuation), optimised the networks via genetic algorithms, and evaluated the reliabilities with simulation. Recently, Sirsant et al. (2023) made a comprehensive review of related reliability definitions and estimation methods.

Previous contributions rely mainly on stochastic or simulation-based estimation or require expert knowledge for manual model generation. When used for synthesis and retrofitting, they usually generate a single solution, which may be insufficient for adequate decision-making. A deterministic and more systematic method can be developed by exploiting the water transportation systems' structure (i.e., the presence and connectivity of their elements), since it has a critical role in defining properties such as reliability and resilience. Hence, the P-graph framework has been proposed as a basis for calculating these indicators. This framework exploits the properties of the superstructure that represents the problem to find the n-best solutions to it (Friedler et al., 2022). The framework's algorithms and its unambiguous representation of processes can handle various systems and model types. Thus, it has been used to address numerous complex design problems, including supply chains (Cabezas et al., 2018), carbon management networks (Migo-Sumagang et al., 2022), and production scheduling (Kalauz et al., 2024). Naturally, the P-graph framework is capable of handling the structure of water transportation systems as well as modelling their flow constraints. Recently, deterministic reliability calculation methods were developed with the P-graph framework (Kovács et al., 2019), which can be applied to any network that is modelled with the P-graph. It is applicable to water transportation systems. The method can be integrated into process synthesis as well (Orosz et al., 2023). However, no previous contribution has introduced a systematic approach that utilises deterministic reliability calculation methods for the retrofitting of water transportation systems, generating the n-best designs for it.

This work presents an algorithmic approach for retrofitting urban wastewater transportation systems capable of generating a range of alternative designs for enhancing their reliability. The approach developed relies on the aforementioned methods based on the P-graph framework to calculate the reliability of urban water transportation networks, considering potential failures. Consequently, the set of n-best solutions can be generated, contemplating both the investment cost of the retrofit and the reliability of the final design. This set of solutions provides decision-makers with a range of retrofit designs that reduce the system's vulnerability to failures and convey information about the trade-offs between investment and reliability. It is expected that the insightful information that decision-makers can retrieve from this set of alternative designs can strengthen wastewater systems and decrease pollution.

2. Methodology

This section presents the methodology proposed to find retrofitting alternatives that improve the reliability of wastewater transportation systems. The method developed is rooted in the P-graph Framework (Friedler et al., 2022), which relies on the properties of the structure representing the system to enhance the process of finding alternative designs. Because of its capacity to exploit the properties of the structure, the framework can deliver a set of the n-best solutions to the synthesis problem (i.e., designs) and carry out a rigorous enumeration of the processing alternatives. This last faculty of enumerating processing alternatives has been utilised to analyse the structural properties of the system, including reliability and resilience. Evaluation of structural reliability of

systems consists of enumerating the possible failure combinations of the system, finding the operational sub-structures, and calculating their probability of occurrence. Here, a sub-structure of the process structure is operational if it is capable of performing its designated process, at least to a prespecified level. Since a first requirement of operational sub-structures is to have a sub-network that fulfils the combinatorial axioms upon which the P-graph is based, the enumeration of operational structures can be performed by employing the P-graph algorithms (Friedler et al., 1992). From that, the general reliability formula (Kovács et al., 2019) is applied to determine the reliability.
The methodology proposed here is based on the methods developed by Orosz et al. (2018). The methodology developed has the objective of generating a set of retrofitting alternatives for wastewater transportation systems with enhanced reliability. Figure 1 summarises the major steps proposed. The retrofitting alternatives considered here uniquely contemplate the possibility of extending the existing infrastructure, i.e., the base structure, of wastewater transportation systems. The method starts by defining the plausible operating units considered to extend the system. This involves determining operating units, such as emergency storage and alternative pumping systems, capable of handling possible failures in the base structure. As a part of such a definition, the investment cost of the extension units and their individual reliability must be specified.

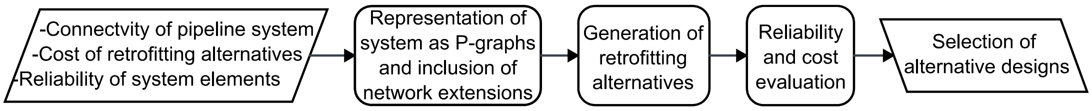

Figure 1: Methodology to generate reliable retrofitting alternatives for wastewater transportation systems

Subsequently, all elements in the system are represented as P-graphs. For this, the units in the system are depicted as horizontal bar nodes, and their inputs and outputs (i.e., material streams) are depicted as circle nodes. Both types of nodes are connected to each other by means of arcs that indicate the flow of material in the system. From this structure, the retrofitting alternatives can be generated by enumerating the distinct combinations of the extension units and including them in the base structure. Then, the total cost of the extension and the reliability of each alternative design can be individually assessed. As previously mentioned, the evaluation of the alternatives' reliability involves identifying their operational sub-structures.
This identification comprises three steps. First, all sub-structures in each retrofitting alternative are enumerated to determine its possible states (i.e., all possible combinations of failed and operative units). Each possible sub-structure represents a plausible state of the system. Second, the algorithm MSG of the P-graph framework (Friedler et al., 1992) is utilized in each of these sub-structures. This algorithm detects whether a structurally feasible sub-network exists in the particular system's state, i.e., exists a sub-network that satisfies the framework's combinatorial axioms. If the system state contains no structurally feasible sub-network, then the structure representing such a state cannot be operational. These sub-structures (i.e., states) are not further considered. Third, if a structurally feasible sub-network exists, the state is examined in light of the feasibility model. This model comprises the mass balance in the transportation system, as well as the flow and capacity constraints. Moreover, the maximum amount of wastewater that is not transported to its destination is restricted by placing a constraint on the system's overflow. The existence of a solution for the feasibility model implies that the state evaluated is still capable of delivering a prespecified minimum of wastewater into the treatment plant despite its failures. The state constitutes an operational sub-structure.
The retrofitting alternative's reliability (r) is calculated via the reliability formula, this is

$$r = \sum_{(x_1,x_2,\dots,x_n)\in U} \left(\prod_{i=1}^{n} p_i^{x_i} (1-p_i)^{(1-x_i)} \right) \tag{1}$$

where U is the set of operational states of the retrofitting alternative. The states are represented as vectors of binary variables, x_i, that take the value of zero if the unit i has failed, or one otherwise; p_i is the reliability of unit i, and n is the number of units in the retrofitting alternative. Once all retrofitting alternatives have been evaluated in terms of cost and reliability, the set of best designs (non-dominated solutions) can be retrieved.

3. Case Study

The case study considers an urban wastewater system that treats approximately 1.6 million gallons of wastewater per day. The system consists of eight pumping stations (A, C, D, E, G, H, I, M) that recover the wastewater from different regions via the sewage system. They are interconnected through pipelines that transport the wastewater to the treatment plant (WWTP). In the current system (i.e., the base structure), pumping stations E, I, and M send wastewater to pumping station D; H and G are connected to pumping station M; and stations D, A, and C are connected to the WWTP. Figure 2(a) shows the connectivity of the system's elements. In this figure, it is noted that the system has no redundancies. Thus, if a pipeline fails, no alternative path exists. Because of this configuration, transport between pumping stations D and M becomes critical, as any failure would result in a major loss of wastewater. Consequently, alternative paths are introduced between D and M, between D and the WWTP, and between M and the WWTP. Tanks are added to store the wastewater in case of an overflow of water or a pipeline breakdown at pumping stations A, C, E, G, H, and I. Figure 2(b) shows the modified pipeline. The values of cost, reliability, and maximum flow used for the pipelines (P) and pumping stations (PS) utilised in the case study are shown in Table 1. Herein, only the investment cost of the retrofitting alternatives is considered. Only the extension pipelines (P9 to P11) have purchase and installation costs.

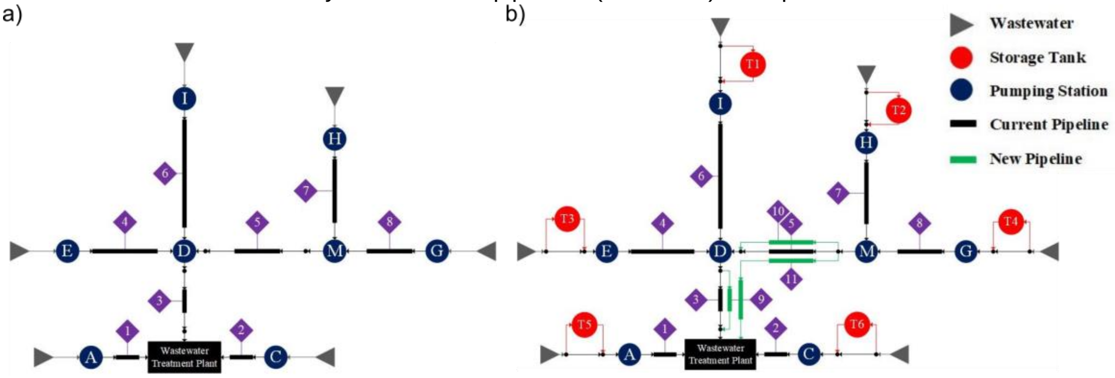

Figure 2: Connectivity of basic wastewater transport network (a) and structure with proposed modifications (b)

The units representing storage tanks in the problem (T1 to T6) are assumed to have an annualised investment cost of 62,400 USD/y, a maximum capacity of 250,000 gal, and a reliability of 0.95. The reliability examination for this case study is carried out considering a time horizon of 1 day. Therefore, 1.66 million gal should be transported by the wastewater transport system. The volume of water to be transported from the distinct sources is shown in Table 2.

Table 1: Annualized cost (kUSD/y), maximum flow (MF in thousands of gal/d), and reliability (R) of units in case study

Unit	Cost	MF	R	Unit	Cost	MF	R	Unit	Cost	MF	R
P 1	0	860	0.810	P8	0	310	0.776	PS E	0	500	1
P 2	0	860	0.843	P 9	123.6	860	0.995	PS G	0	500	1
P 3	0	1,200	0.748	P 10	34.4	550	0.995	PS H	0	500	1
P 4	0	860	0.689	P 11	108.7	550	0.995	PS I	0	500	1
P 5	0	700	0.873	PS A	0	500	1	PS M	0	500	1
P 6	0	310	0.493	PS C	0	500	1				
P 7	0	138	0.653	PS D	0	1,200	1				

Table 2: Volume of wastewater to be transported from each region (thousands of gal)

Source	Region A	Region C	Region E	Region G	Region H	Region I
Flow	350	320	410	250	110	220

The P-graph structure of the system constructed by these units is shown in Figure 3. In this figure, the nodes of the basic structure are depicted in black, whereas those of additional tanks are presented in red, and the ones of additional pipelines are shown in green.

This structure, as well as the data on cost and reliability, are used with the method explained in Section 2 to generate retrofitting alternatives. The method was implemented in Python V3.9, and the feasibility model was verified using the model of the software P-graph Studio (P-graph community, 2015). Two additional product nodes are included in the P-graph representation to evaluate the system's feasibility using this model. Specifically, in addition to those representing the wastewater destination, a product node is included to represent the system's overflow (presented in blue in Figure 3), whereas the second one, denoted as "Requirement" in Figure 3, is utilised to guaranteeWS that all sources of wastewater are considered in the problem. These nodes are connected to the source nodes by means of condition verifier nodes, which are shown as blue horizontal bars. In this case study, the maximum overflow of an operational structure was defined as 166,000 gal.

As a result of the examination, 512 distinct designs are evaluated. Figure 4 shows a plot of the reliability and investment cost of the generated solutions.

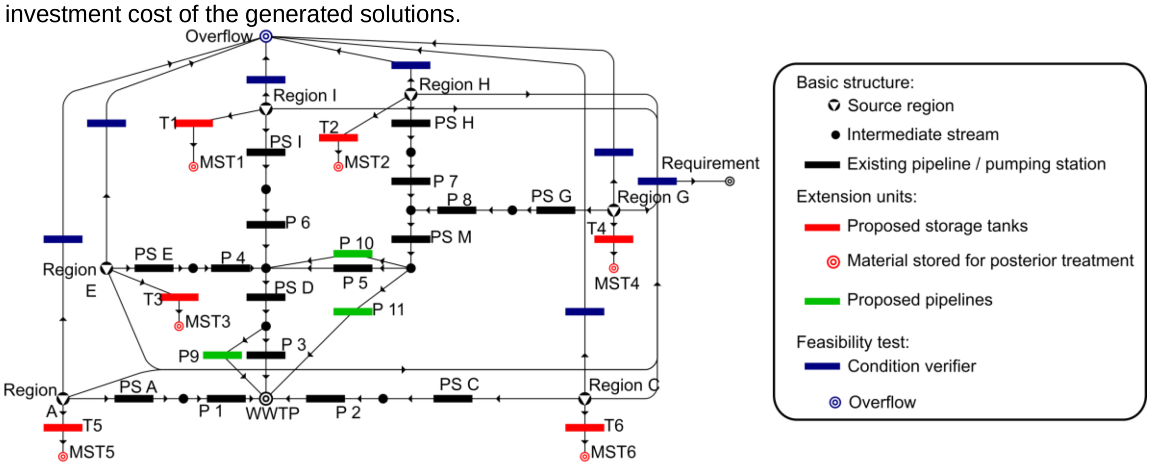

Figure 3: P-graph representation of wastewater transportation system in the case study

In this figure, the best solutions in terms of these two indicators are shown as yellow diamonds, whereas the additional solutions are shown as blue circles. Table 3 lists the units, including the reliability and the cost of some proposed designs in the set of non-dominated solutions generated by the method.

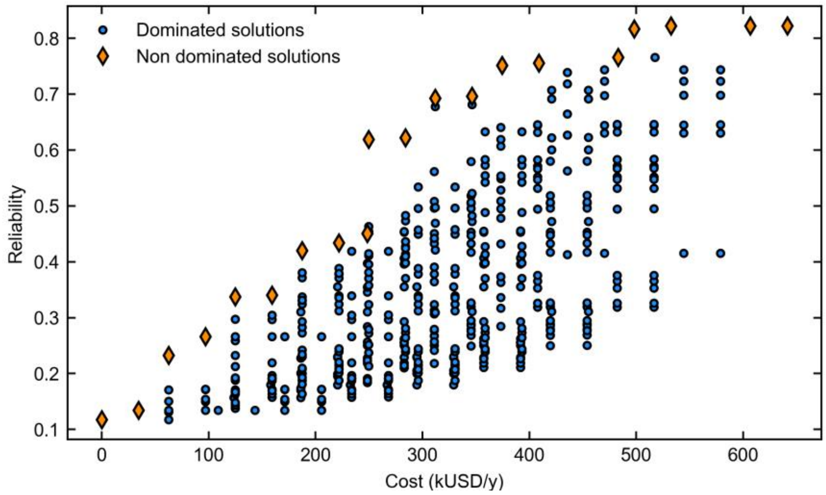

Figure 4: Illustration of set of solutions for retrofitting wastewater transportation system in case study

Table 3: Description of some non-dominated retrofitting alternatives generated. Cost is presented in kUSD/y

Additional units	Reliability	Cost	Additional units	Reliability	Cost
T4, T2, T6, T5, T3, P_9, P_10, P_11	0.822	641.2	T4, T1, T2, T3	0.619	249.6
T4, T2, T6, T1, T5, T3, P_9, P_11	0.822	606.7	T4, T1, P_9	0.450	248.4
T4, T2, T6, T1, T5, T3, P_10	0.755	408.8	T4, T1, T3	0.420	187.2
T4, T2, T6, T1, T5, T3	0.751	374.4	T4, T1	0.337	124.8
T4, T2, T1, T3, P_10	0.622	284.0	None	0.118	0

Naturally, the highest reliability (0.822) is reached when all alternative units are included. However, this also results in the highest expense (641.2 kUSD/y). Conversely, the lowest cost occurs when no additional unit is included. This scenario yields a cost of zero and basic reliability for the case study of 0.118. From the set of solutions presented in Table 3, decision-makers can analyse the tradeoffs between investment and reliability. For instance, including tanks 1, 3, and 4 improves reliability by a factor of almost 3.5, with a cost approximately 70% lower than one of the most reliable designs. The addition of all tanks results in a reliability of 0.751 and a total cost of 374.4 kUSD/y. Thus, this structure achieves 91 % of the reliability of the most reliable alternative with 58 % of its investment cost.

4. Conclusions

This work presents a retrofitting methodology for wastewater transportation systems where the retrofitting options include both additional pipelines around the critical parts of the network as well as storage options to act as a short-term buffer. The reliability of each feasible extension option is evaluated along with their cost, and a set of 20 non-dominated alternatives was determined. While the most reliable designs are expensive, by carefully selecting the extension to build, it is possible to achieve 75 % of the highest reliability with just 39% of the cost or 91 % of the reliability with 58 % of the cost. The case study demonstrates the applicability of the method developed and illustrates its potential to decrease wastewater transportation networks' vulnerability to failures. The method introduced requires computing the individual system’s elements' reliabilities beforehand; however, defining these reliabilities based on the system’s properties is not simple. Future work can focus on determining them via data-driven approaches or in the introduction of uncertainties for these parameters.

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