Optimization Techniques for Rehabilitating Water Distribution Networks

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Abstract. Water sustainability ensures clean and plentiful water for both current and future generations. Water is the core of sustainable development as it is critical for socio-economic development, healthy ecosystems, and for human survival itself. It helps companies address supply and demand issues by using water more efficiently as well as reducing the amount of water needed to manufacture their products. Maintaining water sustainability is difficult because of a high level of non-revenue water (NRW) or water losses in water distribution networks (WDN). While one of the significant causes of NRW in Malaysia is difficulties in rehabilitating WDN, studies on effective approaches for rehabilitating WDN is limited. So, it is essential to understand the optimization techniques for rehabilitating WDN. Hence, this study’s objective is to identify the different optimization techniques for rehabilitating WDN by systematically reviewing the existing literature on WDN rehabilitation. This research contributes to the body of knowledge in providing insights on optimization techniques for WDN rehabilitation, which could help researchers and industry practitioners reduce NRW and achieve water sustainability.

1. Introduction
Water sustainability means that the current and future generations have the accessibility of water to utilize and enjoy. Water sustainability is not only essential for sustainable development, but it is also crucial for human survival, socio-economic development, and healthy ecosystems as well. Therefore, finding approaches towards water sustainability is crucial for national economic and social development.

To reach water sustainability, water losses represented in Non-Revenue Water (NRW) should be reduced; NRW is the water that is produced and lost before it reaches the customers. NRW is one of the trending problems in the world [1]. Malaysia experienced an average NRW of 35% per year from 2014 to 2017 [2]. In other words, these numbers illustrate that there a considerable amount of lost water in Malaysia’s water distribution system [2]. Therefore, decreasing NRW plays an essential role in reducing water losses resulting in taking crucial steps towards water sustainability.
Rehabilitating the water distribution network (WDN) is one of the ways to decrease NRW as old or poorly constructed pipes have a higher percentage of water leakage than new and well-constructed pipes. WDN is also known as the water distribution system. WDN rehabilitation is the repair or replacement of water pipes that run under a town or a city, offices, industries, and connecting homes to the municipal water connection. WDN rehabilitation involves complex decision-making as the process requires analyzing multiple situations so that the final decision would be optimal as the pipes are buried underground and wrong rehabilitation decisions result in a waste of both time and money [3]. WDN rehabilitation would not only increase service quality but also would contribute to decreasing overall NRW by decreasing water losses among pipes [4].

This paper’s objective is to identify the different optimization techniques for rehabilitating WDN. To achieve that objective, this paper systematically reviews existing articles on rehabilitating WDN. This study contributes to the body of knowledge by providing information on the current practices for rehabilitating WDN. Understanding the best practices for optimizing WDN rehabilitation can help researchers and industry practitioners in making optimal decisions and suitable actions towards lowering NRW, moving towards water sustainability.

2. Research Overview

2.1 Water sustainability

Sustainability is a convoluted concept. The standard definition of sustainability comes from the United Nations World Commission on Environment and Development; “sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [5]. On the other hand, the challenges in water sustainability are (1) Population and (2) The amount of freshwater is getting low.

2.2 Water distribution network (WDN)

WDN is a complicated system that mainly consists of many objects such as pumps, pipes, valves, and a node-set consisting of reservoirs and pipe intersections connections. This network's primary function is serving water within time and with the expected quality to customers [6]. However, many issues can be associated with WDN, such as: (1) interrupted water supply due (2) reduction of carrying capacity of pipes (3) water metering policy(4) water disruption from during peak hours (5) poor record-keeping and proper maintenance of pipes including the network’s system maps and designs; and (6) NRW [7]. From all those challenges, this study focuses on NRW.

2.3 Non-revenue water (NRW)

NRW is the water that is being pumped or produced, but it is lost or unaccounted in the system, associated with theft, evaporation false metering poor data collection, and leakage. In other words, NRW is the difference between system input volume and billed authorized consumption. The International Energy Agency has estimated that 34% of all water worldwide becomes NRW [8]. NRW consists of three components - unbilled authorized consumption, apparent loss, and real loss.

2.4 Rehabilitating WDN

WDN rehabilitation is the process of infrastructure renewal, repair, and replacement technologies to return the functionality to the WDN [9]. There are many challenges to consider the rehabilitation of WDN like (1) economic, which are represented in the costs. Costs can be divided into maintenance costs, operating costs, capital costs and damage costs, (2) the reliability, where its addresses the performance and the service is
available at all the time without interruptions, and (3) water quality, which consider the changes in water chemical properties that are being transported in pipes as it gets older and deteriorates by the time [10].

3. METHODOLOGY

In this study, a systematic review was adopted to identify and analyze the optimization methods and techniques for rehabilitating WDN. This systematic review consisted of three stages. In the first stage, a comprehensive search is conducted under “T/A/K (title/abstract/keyword).” This study uses Scopus as the search engine, as it covers a wide range of databases and contains high impact journals. The search involves the following keywords: (1) “water”; and (2) “pipeline” OR “pipe system” OR “water distribution” OR “water network” OR “water supply network” OR “distribution network” OR “supply system OR water main”; and (3) “rehabilitate” OR “renew” OR “repair” OR “reconstruction” OR “maintenance” OR “restoration” OR “replacement” OR “fix” OR “renovate” OR “re-establish.” Also, this study limits the results to only articles and review papers that are both in the final version and English. Then, we limited the search to the subject areas that are appropriate to the study, which consists of “engineering,” “business, management, and accounting,” and “decision sciences.” The full search code is:

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TITLE-ABS-KEY ((water) AND (pipeline OR pipe system OR water distribution OR water network OR water supply network OR distribution network OR supply system OR water main) AND (rehabilitate OR renew OR repair OR reconstruction OR maintenance OR restoration OR replacement OR fix OR renovate OR reestablish) ) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "DECI") ) AND (LIMIT-TO (PUBSTAGE, "final") ) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re" )) AND (LIMIT-TO (LANGUAGE, "English")) ) AND (LIMIT-TO (SRCTYPE, "j"))
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The search was on 5/11/2019, with 690 results. Then, the results are refined to journals with at least three papers in rehabilitation methods of WDN, resulting in 327 papers. The 53 journals that are included in this study are: Water Supply, Journal Of Water Resources Planning And Management, Pipes And Pipelines International, Journal Of Pipeline Systems Engineering And Practice, Journal Of Infrastructure Systems, Structure And Infrastructure Engineering, Tunnelling And Underground Space Technology, Journal Of Performance Of Constructed Facilities, Water Bulletin, Journal Of Hydraulic Engineering, Journal Of The New England Water Works Association, Water Resources Management, Civil Engineering And Environmental Systems, Desalination And Water Treatment, Pipe Line Industry Houston Tex, CONCAWE Reports, Canadian Journal Of Civil Engineering, Engineering Failure Analysis, Flow Measurement And Instrumentation, Global Pipeline Monthly, Measurement Journal Of The International Measurement Confederation, Aqua London, Composite Structures, Desalination, IEEE Access, International Journal Of Applied Engineering Research, Ocean Engineering, Offshore, Pipeline Ind Guild J, Proceedings Of The Institution Of Mechanical Engineers Part O Journal Of Risk And Reliability, Sensors Switzerland, Canadian Geotechnical Journal, Civil Engineering London, Eksploatacja I Niezawodnosc, Energy, Fusion Engineering And Design, Hydrotechnical Construction, IEEE Sensors Journal, Irrigation And Drainage Systems, Journal Of Disaster Research, Journal Of Failure Analysis And Prevention, Journal Of Fluids Engineering Transactions Of The ASME, Journal Of Irrigation And Drainage Engineering, Journal Of Loss Prevention In The Process Industries, Journal Of Protective Coatings And Linings, Journal Of Sound And Vibration, Measurement Science And Technology, Petroleum Engineer International, Practice Periodical On Structural Design And Construction, Scandinavian Oil Gas Magazine, Soil Dynamics And Earthquake Engineering, Surveyor, and Welding International.

In the second stage, a visual examination is conducted on the title, abstract, and conclusion to choose suitable papers for the systematic review, which results in a total of ten articles. Then, articles that are
4. RESULTS AND DISCUSSION

Table 1 represents the techniques for optimizing WDN rehabilitation from the 22 articles. In summary, there are 23 techniques, these techniques can be categorized into two main approaches: (1) subsurface construction-based approach; and (2) computer-based approach. The subsurface construction-based approach consists of two methods: (a) molding; and (b) trenchless. Conversely, the computer-based approach involves four main methods: (i) algorithm; (ii) models; (iii) programming; (iv) index.
Table 1. Techniques for optimizing WDN rehabilitation.

| Approach                        | Method                  | Technique                                      | Source |
|---------------------------------|-------------------------|------------------------------------------------|--------|
| Subsurface construction based   | Molding                 | Resin transfer molding (RTM)                   | [11]   |
|                                 |                         | Slipping                                       | [12]   |
|                                 | Trenchless              | Cured-in-place lining                          | [12]   |
|                                 |                         | Pipe bursting                                  | [12]   |
|                                 |                         | Pipe ramming (PR)                              | [12]   |
|                                 | Algorithm               | Hybrid genetic algorithm model (HGA model)     | [13]   |
|                                 |                         | Non-dominated sorting genetic algorithm        | [14]   |
|                                 |                         | Genetic algorithms                             | [10]   |
|                                 |                         | Multi-objective genetic algorithm (MOGA)       | [15],[16],[17],[18],[19],[20] |
|                                 |                         | Structured messy genetic algorithm             | [21]   |
|                                 |                         | Strength Pareto Evolutionary Algorithm (SPEA)  | [20]   |
| Computer based                  | Models                  | Replacement Decision Optimization Model for Group Scheduling (RDOM-GS) | [22]   |
|                                 |                         | Prioritisation models                          | [28]   |
|                                 |                         | Optimisation models                             | [28],[29],[30] |
|                                 |                         | Reliability models                             | [28]   |
|                                 |                         | Water quality models                           | [28]   |
|                                 |                         | Economic models                                | [28]   |
|                                 |                         | Operational models                             | [28]   |
|                                 |                         | Hydraulic models                               | [28]   |
|                                 | Programming             | Mixed-integer nonlinear programming             | [26]   |
|                                 |                         | Dynamic programming                            | [23],[24],[25] |
|                                 |                         | A multilevel decomposition scheme              | [27]   |
|                                 | Index                   | Significance index (SI)                        | [31]   |

4.1. Methods for subsurface construction-based approach

4.1.1 Molding.

In addition to causing traffic congestions and a large amount of waste, excavating during the process of repairing and replacing WDNs requires heavy machinery and longer operating time and cost. While there are trenchless technologies, most of the technologies involve high construction cost, inconvenience of operation, and limited application to circular conduits. To address those disadvantages, this technique - resin transfer molding (RTM) is a process for reinforcing retired or repairing damaged WDNs using fiber-reinforced composite materials [11]. The technique also involves applying appropriate and vacuum during the process of reinforcing the WDNs [11]. RTM requires shorter operational time, lower costs, and less operating equipment than conventional trenchless technologies that increase the compressive load capacity [11]. Also, RTM can increase the reinforced strength of the pipes up to 15% [11].
4.1.2 Trenchless.

There are several methods regarding trenchless techniques of WDN rehabilitation. First, slip lining is one of the oldest ways of water pipes rehabilitation. A slipping method consists of a small diameter pipe being inserted in a deteriorated host pipe and the annulus between the existing pipe and the new pipe is grouted.

Second, cured in place pipes (CIPP) is the use of polyester or epoxy resin-impregnated fabric tube. The tube is injected into the existing host pipe and inflated against the host's wall using a hydrostatic head or air pressure. Third, pipe bursting typically utilizes a percussive tool, static expansion cone, or a hydraulic expander to break out the existing pipe, while a new pipe is pulled in place. Forth, pipe ramming (PR) is a trenchless method that allows installing new pipes under roadways from a drive to a reception shaft utilizing the dynamic force and energy transmitted by a percussive hammer attached to the end of the pipe (like pile driving). PR permits the installation of a larger casing in a wide range of soil conditions.

Every project is unique, so it is critical to evaluate the trenchless technique system on a project to project basis by considering each criterion and sub-criterion importance for the final decision task. The criteria are divided under five basic categories, need-based criteria, economic criteria, technological criteria, project-specific criteria, and safety/risk criteria. Furthermore, the sub-criteria includes labor intensity, the repetitiveness of work, critical to productivity achievement, quality, high production, labor savings, health hazards, and physical hazards. A support system would assist in the decision process by systematically evaluating five groups criteria and sub-criteria that will lead to optimal decision-making after comparing each technique. The system's strengths for the process of selection are being able to analyze quantifiable and intangible decision criteria and the determination of the most suitable option based on priority.

4.2 Methods for computer-based approach

4.2.1 Genetic algorithms (GA)

Genetic algorithms are a type of optimization algorithm, meaning they are used to find the maximum or minimum of a function. Most papers identified in this study are associated with GA. The main differences between GA and traditional search and optimization procedures are: (1) GA involves coding both traditional and new parameters while conventional methods only involve traditional coding parameters; (2) GA analyzes multiple points while conventional methods analyze single points, (3) GA uses only payoff to achieve its objective function while traditional methods use both payoffs and derivatives; (4) GA consist of probabilistic models while traditional methods are fully deterministic models; and (5) GAs are inherently parallel that resulted in the main strength of GA on dealing with a large number of random points random.

The advantages of this method are it can identify and schedule pipe replacement in a deteriorating WDN, provide optimal scheduling of leakage detection and pipe replacement in WDN, improve the carting capacity of WDN, and minimize overall costs of the rehabilitation over a fixed time.

4.2.2 Models

Techniques in this method include the application of a replacement decision optimization model for group scheduling (RDOM-GS). It consists of three parts. First, the pre-analysis aims at divining the probability of failure for each pipe at each age using a hazard prediction model. Second, the group scheduling criteria analysis which concentrates on decreasing the possible group scheduling options by considering multiple group-scheduling criteria. Third, the cost model and the service interruption model consider group scheduling of pipes by calculating cost savings and the reduction of service interruption results. This technique helps to minimize both total cost and service interruption besides that it also has vital benefits that should be considered by water utilities through the implementation of RDOM-GS. The application can potentially be extended to other networks such as railway, road networks, and electricity distribution.
Prioritization models attempt to prioritize the mains requiring rehabilitation such that, for a given budget, the amount of the likely works can be identified. Optimization techniques consider the relation of each main with the system as a body. They allow cost and performance factors to have an important role in formulating the rehabilitation program. In economic models, any rehabilitation decision should consider all costs that will be carried throughout the WDN lifetime. Reliability models consider the hydraulic reliability of the water distribution system. Hydraulic models which model the deterioration of the hydraulic performance and possible improvement in individual assets. Water quality models are considered the most complex analysis included in the rehabilitation decision. This model could not be used to determine the rehabilitation actions due to this as the consideration of water quality is limited. Operational models considered the trenching and no dig options to rehabilitate of water pipes based on many factors such as road surface, soil classification and surge analysis. The rehabilitation strategy mentioned that a decision model must include many economic criteria upon selection such as reliability of water, hydraulic and quality [28]. The models minimize the expected annual cost during the planning period, generates gest solutions during the deteriorating stage. The model method helps in cost savings, decrease in service interruption, functions representing the risk of pipe breaks and product between the number of bursts and costs associated with future breaks.

4.2.3 Programming
The mixed-integer nonlinear programming is a mixed-integer nonlinear programming problem that adapts a solution procedure that combines an implicit enumeration scheme using a branch and bound algorithm along with a generalized reduced gradient procedure to solve a nonlinear subproblem. This program will help in determining the minimum cost and replace pipes in water distribution networks [26].

The second technique is the Multistage procedure for rehabilitation analysis of water distribution systems (P RAWDS) is based on a dynamic programming approach combined with partial and (sometimes) implicit enumeration schemes [22]. (P RAWDS) has a significant cost saving and reduced service interruption procedure for rehabilitation analysis of WDN [22] and minimize the rehabilitation investment and maintenance costs over time [25]. The advantages of (P RAWDS) are its ability to (1) explicitly consider the deterioration over time of both the structural integrity and the hydraulic capacity of the pipes in the WDN; (2) compare projected cost streams that are independent of the selected analysis period (by considering rehabilitation cycles to infinity); (3) consider the economics and performance of the entire network while regarding each pipe as a separate entity with its characteristics and parameters; and (4) determine each rehabilitation action not only by the current state of the system but by future rehabilitation actions as well. However, it is suitable for relatively small distribution systems with present computational techniques and equipment [24]. This technique has its strengths such as: differentiates between two kinds of rehabilitation measures, i.e., first measures that enhance both hydraulic capacity and structural integrity of pipes and second measures that improve only the hydraulic capacity of the pipe. It can find an optimal approach to identify a minimum cost solution in an ample combinatorial solution space and it is a methodology that takes the time dimension as a consideration to develop a rehabilitation action not only considering current state but also future optimal rehabilitation actions.

The last technique is a multilevel decomposition scheme; it is a multilevel decomposition scheme developed for water distribution systems, which contributes to determining the best resource allocation among the main pipes to maximize the overall system [27]. This technique considers four kinds of costs, i.e., pipe replacement cost, pipe rehabilitation cost, pipe repair cost, and pumping cost. The concept of the solution methodology in this paper is different, where the strength relies on minimizing the overall cost and maximizing the availability of the system.
4.2.4 Index

The significant index is a simple optimality criterion, which is a dimensional index defined as shown in Equation 1. \( S_f = \frac{LQ}{CD} \)

where \( L \) = length of the pipe (in m), \( Q \) discharge in the pipe (in m\(^3\)/s), \( C \) = Hazen-William coefficient, and \( D \) = diameter of the pipe (in m).

This index can be used in an effective way to rehabilitate an existing network as it pointed out that none of the other models managed to handle complex networks. This method is both for the design of new networks and for the rehabilitation of old ones. It is suggested to be applied to identify optimal designs of new networks after being modified slightly.

4.3. Constraints of each optimization method

Table 2 shows the constraints of each optimization method for rehabilitating WDN identified through this paper’s systematic review. The first constraint is that the high price/funding constraints to adopting the optimization techniques. The second constraint is in the optimization techniques' generalizability, which includes many issues like the limitation of applications, some assumptions, delivering water, flow demands, and head conversation. While this type of constraint may not have a solution at the time of the research is done, current technology might overcome that constraint. While the third constraint is that the unavailable data to validate the proposed technique, this sort of data must be available for researches/students or anyone who studies in this field. Finally, the fourth is that there can be associated with the applicability of the optimization techniques. Different methods are appropriate for different rehabilitation situations and might not be optimal for other conditions. In other words, every situation has its own optimal rehabilitation decisions.

| Approach                     | Method   | Constraints | Cost | Generalizability | Applicability | Validity |
|------------------------------|----------|-------------|------|------------------|---------------|----------|
| Subsurface Construction-Based| Molding  | ✔           | ✔    |                  |               |          |
|                              | Trenchless| ✔           | ✔    |                  |               |          |
| Computer-Based               | Algorithm| ✔           | ✔    |                  |               | ✔        |
|                              | Models   | ✔           | ✔    |                  |               | ✔        |
|                              | Programming| ✔    | ✔    |                  |               | ✔        |
|                              | Index    | ✔           | ✔    |                  |               | ✔        |

5. CONCLUSION

This paper aimed to identify optimization techniques for rehabilitating WDN to decrease overall water losses through pipes (NRW) by systematically examined 22 articles that have discussed rehabilitation methods of WDN. From the review, 23 techniques of the WDN rehabilitation are identified and classified according to the authors’ point of view into two main categories, i.e., subsurface construction-based and computer-based, as shown in the following figure2. Most papers used either of case studies or simulation methods as their methodology through their study. Most of the papers focused on minimizing the total cost besides any other factor like reliability, performance, rate of a pipe break, reduce the volume of the unserved water demand over a fixed time, economic efficiency, and stability of pipe flow velocity. The computer-based techniques had the major percentage of reviewed papers, about 90% of documents that show that a computerized-based program will be the best choice to determine the optimal rehabilitation technique to minimize costs and increase performance. The list of techniques can assist industry practitioners in reducing NRW through rehabilitating WDN.
A comparison between each method is conducted to highlight the systematically reviewed papers' main strengths and weaknesses/constraints. Like many other review papers, this paper had fundamental limitations that affect the generalizability of the research findings. The major limitation here in this research is the limited number of documents identified and selected for analysis. This number may not cover other related studies and could help in creating some bias, although the research results would still be helpful and useful for future studies. It is suggested for any further studies to focus more on computerized methods, specifically, the genetic algorithm which since various studies are considering this technique as the most effective approach in minimizing costs and increasing reliability during the rehabilitation process of WDN.

*Note: RDOM-GS=Replacement Decision Optimization Model for Group Scheduling*
6. Reference:

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