IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

Optimization Techniques for Rehabilitating Water Distribution Networks

To cite this article: A M Farouk *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **641** 012019

View the article online for updates and enhancements.

This content was downloaded from IP address 197.37.68.151 on 10/02/2021 at 07:26

IOP Conf. Series: Earth and Environmental Science **641** (2021) 012019 doi:10.1088/1755-1315/641/1/012019

Optimization Techniques for Rehabilitating Water Distribution Networks

A M Farouk[1], N S Romali[1], R A Rahman[1, 2] and M A Seman[1]

1 Faculty of Civil Engineering Technology, Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300 Kuantan, Pahang, Malaysia
2 Earth Resources and Sustainability Centre, Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300 Kuantan, Pahang, Malaysia
E-mail: abdelrahman.mfarouk@gmail.com

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 rule in reducing water losses resulting in taking crucial steps towards water sustainability.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

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:

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"))

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 referenced in the collected papers are gathered. This method is adopted to identify articles outside of the designated databases, but still relevant to the topic. The process of identifying the articles involves going through the list of references of the collected papers. This process is repeated using the articles that have been collected to identify another set of articles until there are no new articles to be found. Finally, a total of 22 articles are identified for further analysis. These articles are subjected to the analysis to determine the rehabilitation techniques of WDN. The following graph 1 summarizes the methodology used in this paper.

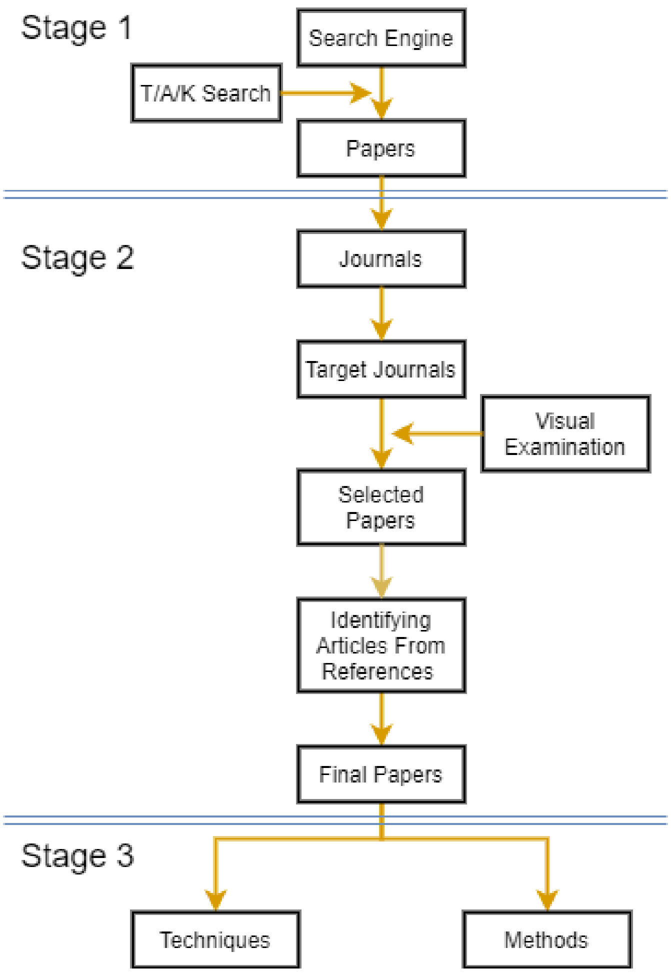

Figure 1. Methodology.

4. RESULTS AND DISCUSSION

Table1 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.

<table>
<tr><th>Approach</th><th>Method</th><th>Technique</th><th>Source</th></tr>
<tr><td rowspan="5">Subsurface construction based</td><td>Molding</td><td>Resin transfer molding (RTM)</td><td>[11]</td></tr>
<tr><td rowspan="4">Trenchless</td><td>Slipping</td><td>[12]</td></tr>
<tr><td>Cured-in-place lining</td><td>[12]</td></tr>
<tr><td>Pipe bursting</td><td>[12]</td></tr>
<tr><td>Pipe ramming (PR)</td><td>[12]</td></tr>
<tr><td rowspan="19">Computer based</td><td rowspan="6">Algorithm</td><td>Hybrid genetic algorithm model (HGA model)</td><td>[13]</td></tr>
<tr><td>Non-dominated sorting genetic algorithm</td><td>[14]</td></tr>
<tr><td>Genetic algorithms</td><td>[10]</td></tr>
<tr><td>Multi-objective genetic algorithm (MOGA)</td><td>[15],[16],[17],[18],[19],[20]</td></tr>
<tr><td>Structured messy genetic algorithm</td><td>[21]</td></tr>
<tr><td>Strength Pareto Evolutionary Algorithm (SPEA)</td><td>[20]</td></tr>
<tr><td rowspan="8">Models</td><td>Replacement Decision Optimization Model for Group Scheduling (RDOM-GS).</td><td>[22]</td></tr>
<tr><td>Prioritisation models</td><td>[28]</td></tr>
<tr><td>Optimisation models</td><td>[28],[29], [30]</td></tr>
<tr><td>Reliability models</td><td>[28]</td></tr>
<tr><td>Water quality models</td><td>[28]</td></tr>
<tr><td>Economic models</td><td>[28]</td></tr>
<tr><td>Operational models</td><td>[28]</td></tr>
<tr><td>Hydraulic models</td><td>[28]</td></tr>
<tr><td rowspan="3">Programming</td><td>Mixed-integer nonlinear programming</td><td>[26]</td></tr>
<tr><td>Dynamic programming</td><td>[23],[24], [25]</td></tr>
<tr><td>A multilevel decomposition scheme</td><td>[27]</td></tr>
<tr><td>Index</td><td>Significance index (SI)</td><td>[31]</td></tr>
</table>

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 [12].

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-criteria 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 [12].

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 [32]. 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[33].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 [22].

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]. These 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. Sf = LQ/(CD)
where L = length of the pipe (in m), Q discharge in the pipe (in m3/s), C = Hazen-Wil1iam 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.

Table 2. Constraints of each optimization method.

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, 23techniques 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.

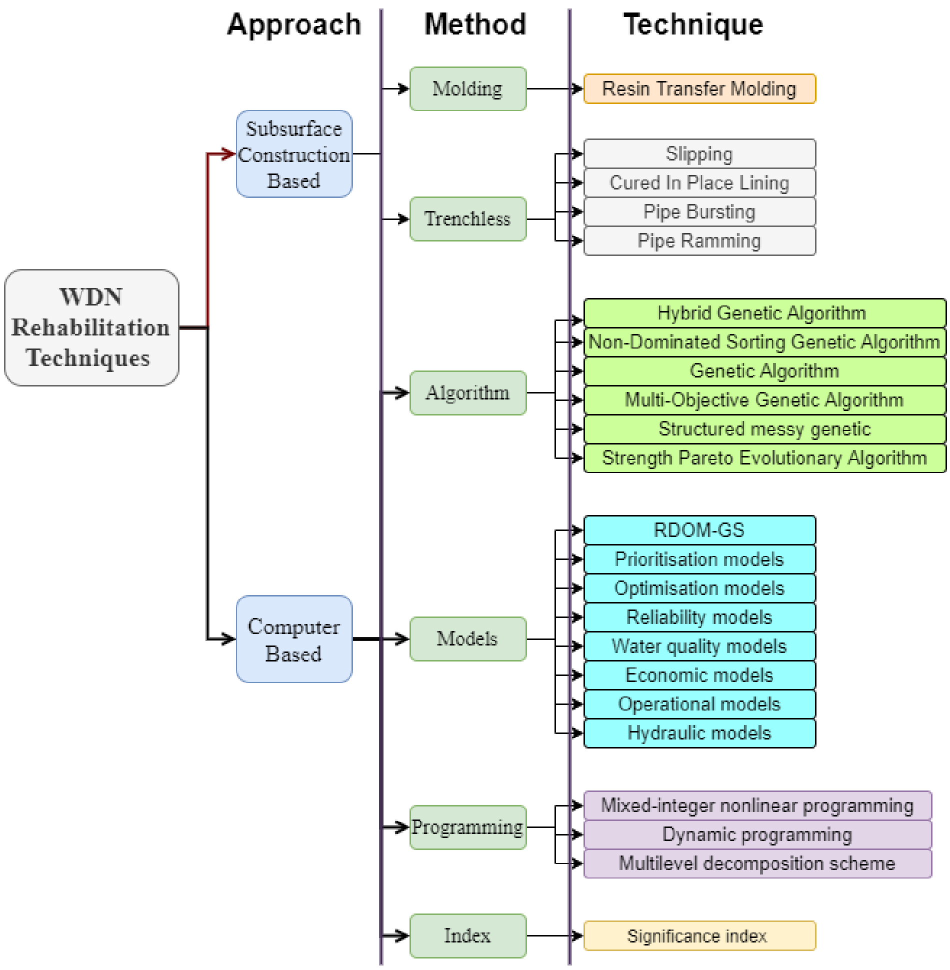

Figure 2. Techniques of WDN rehabilitation.

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

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 algorism 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.

6. Reference:

[1] Van den Berg, C., 2014. The drivers of non-revenue water: *how effective are non-revenue water reduction programs?*. The World Bank.

[2] (http://www.data.gov.my/data/ms_MY/dataset/318f4e33-54ba-4527-a105-8a2fbf9e502d/resource/f35e3c11-905e-44e1-85ff-f202f053df08/download/non-revenue-water-nrw-2014---2017.xlsx).(Accessed 21 December 2019).

[3] Choi, T., Han, J. and Koo, J., 2015. Decision method for rehabilitation priority of water distribution system using ELECTRE method. *Desalination and Water Treatment*, **53**(9), pp.2369-2377.

[4] Güngör, M., Yarar, U. and Firat, M., 2017. Reduction of water losses by rehabilitation of water distribution network. *Environmental monitoring and assessment*, **189**(10), p.498.

[5] https://www.sustain.ucla.edu/about-us/what-is-sustainability/(Accessed 1 December 2019).

[6] Moosavian, N. and Jaefarzadeh, M.R., 2014. Hydraulic analysis of water distribution network using shuffled complex evolution. *Journal of Fluids, 2014.*

[7] Dighade, R.R., Kadu, M.S. and Pande, A.M., 2014. Challenges in water loss management of water distribution systems in developing countries. *International Journal of Innovative Research in Science, Engineering and Technology*, **3**(6), pp.13838-13846.

[8] Ress, E. and Roberson, J.A., 2016. The Financial and Policy Implications of Water Loss. *Journal-American Water Works Association*, ***108***(2), pp.E77-E86.

[9] D'Ercole, M., Righetti, M., Raspati, G., Bertola, P. and Maria Ugarelli, R., 2018. Rehabilitation Planning of Water Distribution Network through a Reliability—Based Risk Assessment. *Water*, **10**(3), p.277.

[10] Dandy, G.C. and Engelhardt, M., 2001. Optimal scheduling of water pipe replacement using genetic algorithms. *Journal of water resources planning and management*, *127*(4), pp.214-223.

[11] Chin, W.S., Kwon, J.W. and Yoo, A.K., 2002. *Repair of underground buried pipes with resin transfer molding. Composite structures*, **57**(1-4), pp.67-77.

[12] Hastak, M. and Gokhale, S., 2000. System for evaluating underground pipeline renewal options. *Journal of infrastructure systems*, **6**(3), pp.105-113.

[13] Arai, Y., Koizumi, A., Inakazu, T. and Koo, J., 2009. Optimization model for water distribution network considering minimization of total replacement cost and], *Economic level of reliability for the rehabilitation of hydraulic networks in pipelines. Desalination and Water Treatment*, **2**(1-3), pp.45-51.

[14] Tricarico, C., Gargano, R., Kapelan, Z., Savic, D. and De Marinis, G., 2006. Economic level of reliability for the rehabilitation of hydraulic networks. *Civil engineering and environmental systems*, **23**(3), pp.191-207.

[15] Alvisi, S. and Franchini, M., 2009. Multiobjective optimization of rehabilitation and leakage detection scheduling in water distribution systems. *Journal of water resources planning and management*, **135**(6), pp.426-439.

[16] Dandy, G.C. and Engelhardt, M.O., 2006. Multi-objective trade-offs between cost and reliability in the replacement of water mains. *Journal of water resources planning and management*, **132**(2), pp.79-88.

[17] Giustolisi, O. and Berardi, L., 2009. Prioritizing pipe replacement: From multiobjective genetic algorithms to operational decision support. *Journal of Water Resources Planning and Management*, **135**(6), pp.484-492.

[18] Dandy, G.C. and Engelhardt, M.O., 2001. Optimum rehabilitation of a water distribution system considering cost and reliability. *In Bridging the Gap: Meeting the World's Water and Environmental Resources Challenges* (pp. 1-10).

[19] Alvisi, S. and Franchini, M., 2006. Near-optimal rehabilitation scheduling of water distribution systems based on a multi-objective genetic algorithm. *Civil Engineering and Environmental Systems*, **23**(3), pp.143-160.

[20] Cheung, P.B., Reis, L.F., Formiga, K.T., Chaudhry, F.H. and Ticona, W.G., 2003, April. Multiobjective evolutionary algorithms applied to the rehabilitation of a water distribution system*: A comparative study. In International Conference on Evolutionary Multi-Criterion Optimization* (pp. 662-676). Springer, Berlin, Heidelberg.

[21] Halhal, D., Walters, G.A., Ouazar, D. and Savic, D.A., 1997. Water network rehabilitation with structured messy genetic algorithm. *Journal of water resources planning and management*, **123**(3), pp.137-146.

[22] Li, F., Ma, L., Sun, Y. and Mathew, J., 2015. Optimized group replacement scheduling for water pipeline network. *Journal of Water Resources Planning and Management*, **142**(1), p.04015035.

[23] Kleiner, Y., Adams, B.J. and Rogers, J.S., 1998. Long-term planning methodology for water distribution system rehabilitation. *Water resources research*, **34**(8), pp.2039-2051.

[24] Kleiner, Y., Adams, B.J. and Rogers, J.S., 2001. Water distribution network renewal planning. *Journal of Computing in Civil Engineering*, **15**(1), pp.15-26.

[25] Kleiner, Y., Adams, B.J. and Rogers, J.S., 1998. Selection and scheduling of rehabilitation alternatives for water distribution systems. *Water resources research*, **34**(8), pp.2053-2061.

[26] Kim, J.H. and Mays, L.W., 1994. Optimal rehabilitation model for water-distribution systems. *Journal of Water Resources Planning and Management*, **120**(5), pp.674-692.

[27] Li, D. and Haimes, Y.Y., 1992. Optimal maintenance-related decision making for deteriorating water distribution systems: 2. Multilevel decomposition approach. *Water Resources Research*, **28**(4), pp.1063-1070.

[28] Engelhardt, M.O., Skipworth, P.J., Savic, D.A., Saul, A.J. and Walters, G.A., 2000. Rehabilitation strategies for water distribution networks: a literature review with a UK perspective. *Urban Water*, **2**(2), pp.153-170.

[29] Hong, H.P., Allouche, E.N. and Trivedi, M., 2006. Optimal scheduling of replacement and rehabilitation of water distribution systems. *Journal of infrastructure systems*, **12**(3), pp.184-191.

[30] Li, D. and Haimes, Y.Y., 1992. Optimal maintenance-related decision making for deteriorating water distribution systems: 1. Semi-Markovian Model for a water main. *Water Resources Research*, **28**(4), pp.1053-1061.

[31] Arulraj, G.P. and Rao, H.S., 1995. Concept of significance index for maintenance and design of pipe networks. *Journal of Hydraulic Engineering*, **121**(11), pp.833-837.

[32] Carr, J., 2014. *An introduction to genetic algorithms*. Senior Project, 1(40), p.7.

[33] Lankhorst, M.M., 1996. *Genetic algorithms in data analysis*. Rijksuniversiteit Groningen.

Acknowledgment
This work is supported by Universiti Malaysia Pahang [PGRS200382].