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Study of Pipe Selection Methods to Be Rehabilitated: A Case Study of Jakarta City

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Abstract. Some water distribution pipelines in Jakarta were built decades ago and are currently in a defective condition. Pipeline network managers must carry out a reactive maintenance strategy by repairing many leaks and rehabilitating defective pipes with limited budgets. The current method of selecting pipes to be rehabilitated does not consider economic aspects and is still subjective. Some of the latest methods from the existing literature have considered economic analysis but are not suitable for conditions of reactive maintenance strategies with limited budgets. For this reason, a new method is proposed by considering the reactive maintenance strategy that is currently implemented and considering budget constraints. The proposed new method is in the form of an optimization model for selecting pipes to be rehabilitated to provide maximum economic benefits with the existing budget constraints. Economic benefits consist of the benefits of reduced leak repair costs and the benefits of increased revenue due to eliminated leaks in rehabilitated pipelines. By applying the optimization model to the selection of pipes to be rehabilitated, it is expected that there will be economic benefits that can increase the rehabilitation budget in subsequent years which will speed up the replacement of defective pipes.

Keywords: *pipe rehabilitation; reactive maintenance; pipe rehabilitation benefits; pipe leak; pipe repair.*

1 Introduction

Water is an essential element for human life, and in 2010 the United Nations stated in [1] that the right to clean water and safe sanitation is a human right. In line with this, the Indonesian government has targeted that by 2030 all Indonesian citizens will have easy access to clean water. However, the fulfillment of clean water for all citizens is not easy and full of challenges. In 2019 the Agency for Increasing the Implementation of Drinking Water Supply Systems (BPPSPAM) in [2] reported that one of the main problems in meeting water needs in Indonesia is the high rate of leakage, which is reflected in the high Non-Revenue Water (NRW). NRW is water that is produced and distributed but does not generate income for the water service manager.

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According to the International Water Association (2011) in [3], the NRW level is affected by several factors including physical leaks in pipelines, unpaid consumption, unaccounted consumption, and under-consumption water meter readings. One of the factors that determine the NRW level in a clean water distribution system is leakage in the piping network. Leakage rates in pipelines rank first as the cause of high NRW. The level of leakage in the pipeline network has been compiled by Kahn (2020) in [4], where the highest level of leakage is at the level of 1.2 leaks/km/year.

It is necessary to carry out a maintenance activity to maintain the condition of the pipeline network. Proper maintenance is carried out in a proactive way so that the pipeline does not experience a failure requiring corrective action. According to Van Zyl (2014) in [5], the dominant maintenance activities in the proactive maintenance type include monitoring the condition of pipeline components, corrosion control, protection of the surrounding environment, checking the condition of the inside of the pipe wall, recording maintenance activities, and other preventive maintenance activities.

The older the pipe, the more frequent leaks occur and the higher the need to rehabilitate the pipes. Therefore, part of the water pipe network system in an area with old pipelines requires rehabilitation. Pipeline rehabilitation is carried out to replace damaged old pipelines with new pipes that are in good condition.

An example of a high leakage rate is in old pipe networks that can be found in one area in the city of Jakarta. The average leak rate of pipelines in one of the areas in the city of Jakarta during the period from January 2017 to March 2020 was at a rate of 1.71 leaks/km/year. The leak rate is at a high level compared to the leak level criteria compiled by Khan (2020), which states that a leak rate above 1.2 leaks/km/year is at a high level.

Before carrying out the rehabilitation of a pipeline or pipeline network, it is necessary to carry out a process of selecting the pipeline to be rehabilitated. The method for selecting rehabilitated pipelines has been implemented by one of the managers of clean water pipelines in Jakarta.

2 Current Method For Selecting Pipes To Be Rehabilitated

Pipeline leaks affect NRW or revenue levels. To provide optimal revenue, it is necessary to consider economic aspects in the form of rehabilitation benefits obtained when selecting pipes to be rehabilitated. The relationship between the condition of the pipeline or the level of leakage in the pipeline to revenue is as shown in Figure 1.

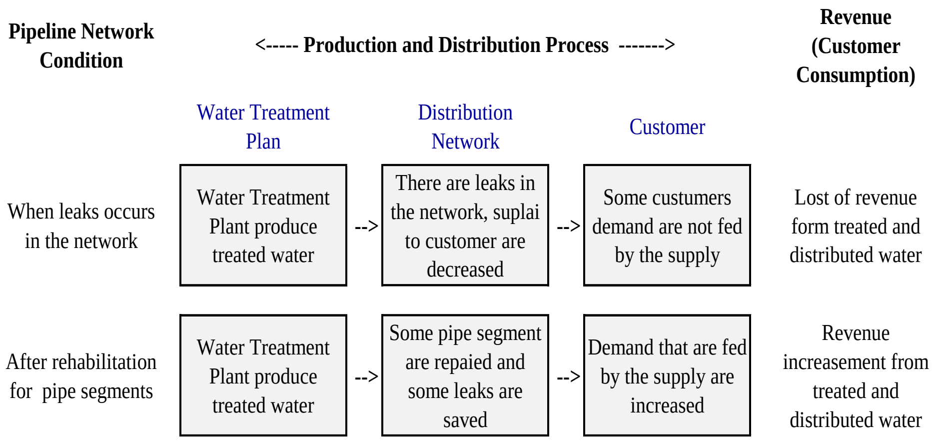

Figure 1 The correlation between pipeline network conditions and revenue

Water treated and produced at a Water Treatment Plant (WTP) is intended for consumption by customers. When leaks occur in the network (shown in the first process line in Figure 1), supply to the customers is reduced so that the customer's consumption becomes less. Loss of water in the pipe network results in loss of income for clean water service managers because some of the water produced is not consumed as expected. After several pipelines were repaired or rehabilitated, the leaks in the pipelines decreased and converted into customer consumption. In the condition after the pipe rehabilitation, the revenue of the clean water service manager increases.

In Jakarta, the selection of pipeline sections to be rehabilitated is based on the results of an assessment of each pipeline's reliability. The assessment of the reliability of the pipeline includes an assessment of several variables, namely pipe age, pipe material, pipe diameter, pipe roughness, and the number of leaks. The determination of these sections does not consider the economic aspect.

In the practice of selecting pipe segments based on the above method, each variable is weighted as follows; pipe material by 20%, pipe age by 25%, the number of leaks by 35%, and pipe roughness by 20%. Each of these variables is assessed qualitatively under certain conditions and ranges as shown in Table 1.

The result of the total assessment is the average score of the four variables considered. Pipe sections assessed are grouped based on the results of the assessment carried out. The grouping consists of 5 categories as follows.

1. Score above 80% = Well conserved, pipes in good condition
2. Score between 60% to 79% = Conserved enough, the pipe is in good condition but has started to decline

3. Score between 40% to 59% = Less conserved, pipe condition decreases with increasing leakage
4. Score between 20% to 39% = Degraded, the pipe condition is getting worse and needs to be rehabilitated
5. Score below 20% = Poorly conserved, critical pipe condition (worst), and rehabilitation priority

Table 1 Ratings on each of the criteria on the currently used method of selecting rehabilitated pipes

Criteria	Indicator	Score
Pipe age	Age = 0 year	1
	Age > 50 year	0
	0 < Age < 50 year	Interpolated
Pipe material	Cast Iron	0.9
	Asbestos Cement	0.6
	HDPE	0.5
	PVC	0.5
	Steel	0.1
	Ductile Cast Iron	0.1
	Galvanized Iron Pipe	0.05
	Others	0.5
Leak number per km	Leaks = 0	1
	Leaks = 0.015	0
	0 < Leaks< 0.015	Interpolated
Pipe friction	Friction > 120	1
	100 < Friction < 120	0.8
	80 < Friction < 100	0.6
	70 < Friction < 80	0.4
	Friction < 70	0

Selected pipes for rehabilitation are pipes with a score below 20% and fall into the poorly conserved condition category. Poorly conserved conditions are critical pipe conditions and are included in rehabilitation priority. Pipelines to be rehabilitated are selected from pipes that fall into this category. This assessment method classifies pipe reliability conditions with available quantitative data. The grouping of pipe assessment result categories is categorized subjectively with certain ranges of values. The selection of pipe sections to be rehabilitated is carried out subjectively from the group with poorly conserved categories.

3 Case Study, Selection of Pipeline to Be Rehabilitated in 2021

3.1 Pipeline Selection

The selection of primary pipelines to be rehabilitated in 2021 is described as follows. The primary pipe is the pipe that carries water from the Water Treatment Plant (WTP) to the distribution pipeline network. A primary pipe is a pipe with a minimum size of 400 mm in diameter. Primary pipes are generally not in an inlet of a District Meter Area (DMA). From the results of the assessment using the method currently used, 186 primary pipelines are categorized as being in a poorly conserved condition, critical pipeline condition, and already on rehabilitation priority. The selection of pipes in poorly conserved conditions to be followed up in the rehabilitation program is carried out by considering other matters which are generally outside the technical aspects. In 2021 a review will be carried out again on the number of leaks that have occurred in each pipeline segment. Of the primary pipes which were assessed as being in a poorly conserved condition, a total of 17 pipes had recorded leaks more than 10 times. The list of the 17 pipes is shown in Table 2.

Table 2 List of pipes that fall into the poorly conserved category with more than ten leaks

No	Segments	Material	Installation Date	Number of Leaks	Final Score
1	Pejagalan Raya	DCI	1985	43	0.17
2	Latuharhari	DCI	1975	38	0.12
3	Margono	DCI	1975	31	0.12
4	Hasyim Ashari	DCI	1985	28	0.17
5	Kali Besar Brt	DCI	1985	27	0.17
6	Kopi 1	DCI	1985	23	0.17
7	Martadinata	DCI	1985	23	0.17
8	Gatot Subroto 3	DCI	1985	21	0.17
9	P. Diponegoro	DCI	1975	21	0.12
10	Wahid Hasyim	DCI	1975	20	0.12
11	Cimahi	DCI	1975	19	0.12
12	Soepomo	DCI	1990	15	0.20
13	Gatot Subroto 2	DCI	1985	13	0.17
14	Gatot Subroto 1	DCI	1985	11	0.17
15	Hayam Wuruk	DCI	1985	10	0.17
16	Kopi 2	DCI	1985	10	0.17
17	Manggarai U. 2	DCI	1975	10	0.12

In 2021, the pipe being rehabilitated is the pipe in line no. 2, namely the pipe on the Latuharhari road with a diameter of 800 mm and a length of 110 meters. The rehabilitation was constructed from 24 June 2021 to 26 June 2021. The assessment was carried out using actual data but in the end, the selection of the pipe to be rehabilitated was made based on certain aspects which were carried out subjectively. The pipe corrosion condition variable is considered important according to Van Zyl (2014) in [5], but in the current assessment, it is not considered.

3.2 Pipe Rehabilitation Results

The results of the rehabilitation can be seen from changes in the flow (amount of flow) flowing in the supply areas of the rehabilitated pipes and changes in pressure (pressure) in the downstream network of the rehabilitated pipelines. After rehabilitation, the pressure on the network in the downstream area of the rehabilitated pipeline increased from 0.2 m to 3.2 m with an average increase of 1.4 m from 5.4 m, and the increase in flow in areas supplied from the rehabilitated pipeline was 12.7 l/s. The changes are based on measurements of conditions before rehabilitation and after rehabilitation. The measurement results are shown in Figure 2.

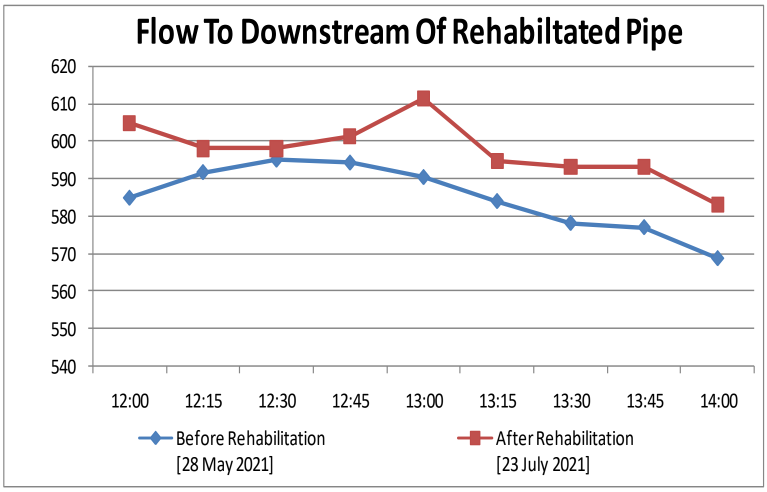

Figure 2 Changes in flow in the pipe before and after rehabilitation

The improvement from the rehabilitation can be seen from the results of flow and pressure measurements in the served area of the rehabilitated pipe. It is indicated that there was an improvement in supply to the areas served by the pipelines. However, it is not yet known how much the resulting increase in revenue will be from the increase in existing supply. The results of this increase have not shown any economic benefits related to NRW.

3.3 Weaknesses of the Selection Method Used

The currently applied pipeline rehabilitation selection method has some weaknesses or drawbacks when applied to the ongoing pipeline maintenance strategy. These weaknesses are as follows.

1. Budget limitations are not accommodated in the method used. Budget constraints generally occur in the reactive maintenance strategy that is currently implemented in pipelines in the city of Jakarta.

2. There is no economic analysis in the current method. Selection of pipes based purely on the physical condition of the pipeline. In reactive maintenance conditions where the rate of leakage is high and the budget for rehabilitation is limited, it is necessary to have a method for selecting rehabilitated pipelines that is more suitable for implementation.

3. The assessment is calculated considering the service life of each pipe material is the same. The determination of the score for pipe age is the same for each pipe material even though the service life for each pipe material is different. For example, the service life of pipes with PVC is shorter than pipes with HDPE material.

4. One of the assessment variables used is pipe roughness which is more closely correlated with the pipe operational capability than the pipe reliability based on physical condition. Pipes with high roughness do not necessarily have poor reliability nor do they necessarily have good reliability. Currently, no research correlates the relationship between pipes with high roughness and pipe damage conditions. In the assessment of this pipe condition variable, the actual results of the investigation on the inside of the pipe that map the corrosion rate of the pipe will more accurately assess the pipe condition constraints compared to the estimation of the pipe roughness.

4 Alternative Methods for Selecting Pipelines for Rehabilitation

Each pipe will suffer a decrease in reliability. Several factors affect the degradation of water pipes. The factors generally considered to have the greatest impact on pipe failure are pipe age, installation period, corrosion, diameter, length, material, seasonal variations, soil conditions, pressure, and nearby excavation as reported by Li (2013) in [6].

According to Li, maintenance is considered a key activity for water utilities to prevent water pipe failures and improve network performance. This maintenance contributes to quality service and enriches all the company's experiences around the services provided. Pipeline managers repair and rehabilitate leaky pipes. Sutjahjo (2021) in [7] stated that pipeline maintenance can be conducted proactively to prevent leaks and reactively carried out after a leak by repairing leaking pipes.

Pipes with poor conditions need to be rehabilitated. Good pipe rehabilitation is carried out with a proactive maintenance strategy, which is to prevent and delay the pipes from being damaged. Some cities have resorted to reactive maintenance strategies. In the reactive maintenance strategy, there are too many leaky pipes so the cost to rehabilitate the leaky pipes is too much compared to the available budget.

Some literature has developed methods for selecting rehabilitated pipelines. Method developed is a model for determining the schedule for the rehabilitation of a pipeline in a proactive maintenance strategy with some literature accompanied by the ability to select the pipeline to be rehabilitated. Currently, a model is needed that can be applied to reactive maintenance strategies with limited budgets to rehabilitate damaged pipes. An overview of the capabilities of the current pipeline selection method, the latest developed models (since 2019), and the proposed model are as follows.

1. *Model of deterioration and optimal rehabilitation modelling for urban water distribution systems*

The model developed by Zhou (2019) in [8] is oriented towards proactive maintenance with the expected research results in the form of a long-term view for multi-objective decision-making by using many variables and disclosing in detail the effect of each of the variables in each module. Unfortunately, the results of this study, which are oriented towards proactive maintenance, cannot be widely used by most pipeline network managers whose maintenance is reactive. As is the case in most other proactive maintenance-oriented studies, the benefits of rehabilitation were not considered in more detail in the form of reduced repair costs and increased consumption from reduced leakage conversions in the rehabilitated pipelines.

2. *Model of economic-based approach for predicting optimal water pipe renewal period based on risk and failure rate*

Kim et al, (2019) in [9] proposed a model by considering the risk factors in the cost-benefit analysis of pipeline rehabilitation. Kim uses failure risk as a failure cost that is included in the cost analysis. The maintenance orientation used is reactive-proactive which brings cost estimates to the cost-benefit analysis which are still in the form of budgetary costs with several assumptions. The results of this study are difficult to implement for the type of proactive maintenance as a whole because there is not much discussion about determining reactive rehabilitation that will affect benefits in the short term.

3. *Model of water pipe replacement scheduling based on life cycle cost assessment and optimization algorithm*

Meanwhile, Ghobadi (2021) in [10] uses the same variables as previous studies, namely data on pipe conditions and pipe leaks, which has considered aspects of the life cycle cost of each pipe segment.

4. *A risk-based approach in rehabilitation of water distribution networks model*

This model was developed by Raspati et al (2022) in [11] to prioritize the rehabilitation of pipelines based on pipeline data and leak rate data. The model is quite simple in that the prioritization of rehabilitated pipelines is risk-based using qualitative risk analysis. The economic aspect was not considered in the research he developed.

Several models for determining rehabilitated pipelines, including those currently in use, have different purposes and capabilities. The ability that is commonly used in general is to predict the future rehabilitation time which is generally required in a proactive maintenance strategy. The models in the proactive maintenance strategy have many incompatibilities when applied to pipeline conditions with reactive maintenance strategies, although some models can determine the priority of several alternative pipelines to be rehabilitated and have economic analysis capabilities. Differences in the capabilities of the current methods with the proposed method are arranged in Table 3.

Table 3 Capabilities on the latest models, the model currently used, and the proposed model

No	Author (Year)	Providing Rehab. Scheduling	Determining Priority For Rehab.	Analyzing The Economic Benefits	Accommodating Budget Limitation
1	Zhou (2019)	√		√	
2	Kim, et al. (2019)	√		√	
3	Ghobadi et al. (2021)	√		√	
4	Raspati et al. (2022)		√		
Current method			√		
Proposed method			√	√	√

Currently, there has not been a single model developed that can accommodate budget constraints on reactive maintenance strategies such as the condition of pipelines in Jakarta. The proposed model cannot predict future pipe rehabilitation schedules in the proactive maintenance strategy that has been developed. However, the new model can be applied to reactive maintenance strategies with a limited budget by considering technical and economic aspects.

5 Pipeline Selection Modeling in Reactive Maintenance Strategy

The methods developed in some of the literature and the methods used today are part of the method for determining rehabilitated pipes using different approaches. These models are not specialized to apply to a reactive maintenance strategy with a limited budget. So, for determining the rehabilitated pipelines on the reactive maintenance type with problems with already high leakage rates, there is an incompatibility in the models studied as follows.

1. All methods of determining rehabilitated pipes above did not consider the condition of a decrease in revenue due to high leakage rates in reactive maintenance types. High leakage causes the pressure to drop and causes the customer's consumption to decrease. In conditions where customer consumption is down and leakage rates are high, rehabilitation of a pipe will lead to an increase in consumption which cannot be ignored. For this reason, it is necessary to develop a model to calculate the benefits of rehabilitation on the increase in revenue due to reduced leakage after rehabilitation.

2. The leakage rate approach in all studied models is estimated for conditions in the distant future with the pipeline still in good condition. This approach cannot be applied to network maintenance with a reactive type when the leakage rate is already very high so the leakage rate is no longer necessary to estimate the condition of the pipes that are still good.

3. All the rehabilitated pipe determination methods in the literature reviewed did not include budget constraints as a direct limitation on the rehabilitated pipe determination model they developed. In the model for determining rehabilitated pipelines for the reactive maintenance type, the limited rehabilitation budget is one of the main influencing variables.

From this mismatch, it is necessary to develop a model that can be applied to reactive types of maintenance with high leakage rates. The conceptual framework of the model corresponding to these conditions can be described as follows.

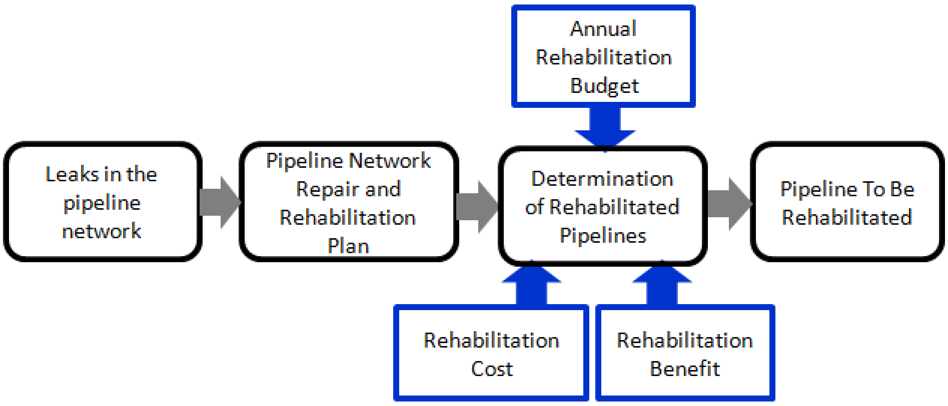

Figure 3 The proposed model conceptual framework

There is a series of processes starting from damage to the pipe, planning for repair and rehabilitation of the pipeline network, and determining the pipeline to be rehabilitated. In the process of determining the pipe to be rehabilitated, the variables that influence it are the rehabilitation budget, rehabilitation costs, and rehabilitation benefits. Some of the existing literature obtained the variables that influence it. The following table presents the influencing variables and how to get them.

Table 4 The calculated variables and their data sources

No	Variables	Sources For Obtaining Information
1	Rehabilitation cost	Annual budget plan
2	Pipe length	Network pipeline database (GIS)
3	Pipe diameter	Network pipeline database (GIS)
4	Rehabilitation unit price	Annual frame contract rate
5	Leaks rate	Network pipeline database (GIS)
6	Cycle time	Network pipeline database (GIS)
7	Repair unit price	Annual frame contract rate
8	Costumer consumption	Customer database
9	Water charge	Local government regulations
10	Leaks in the pipeline	Network pipeline database (GIS) or direct measurement form the field
11	Pipeline network data	Network pipeline database (GIS)

A schematic of the relationship between these variables is obtained in the rehabilitation program of a pipeline network. From the existing literature, the variables and the relationship scheme between these variables are shown in Figure 4.

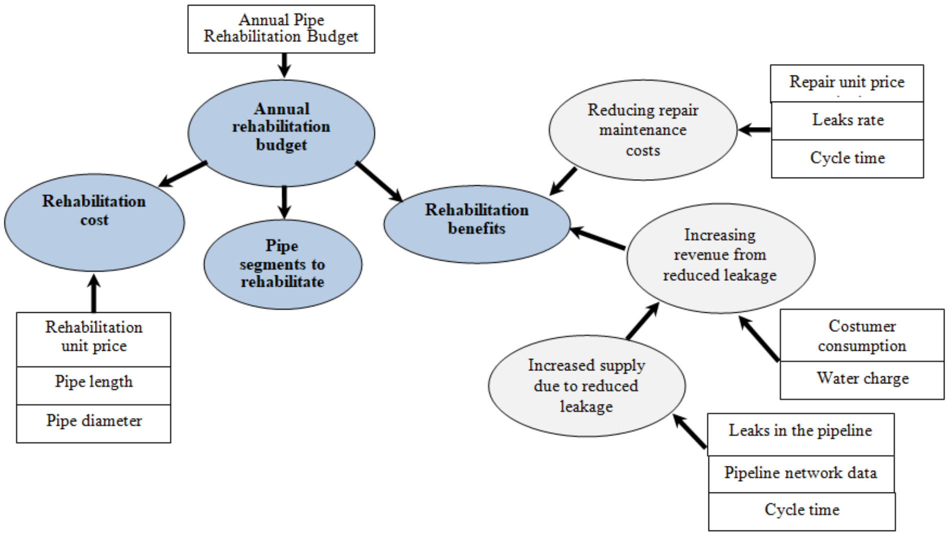

Figure 4 The relationship between variables in the optimization model for selecting pipelines to be rehabilitated

An optimization model for selecting the pipelines to be rehabilitated needs to be developed. The model is based on the relationship scheme between the variables above. The selection of pipe to be rehabilitated is determined by the rehabilitation budget, rehabilitation costs, and rehabilitation benefits.

The main variables considered in the optimization model are the rehabilitation budget, rehabilitation costs, and rehabilitation benefits. In the reactive maintenance type where the leakage rate is very high, a very large rehabilitation cost is required, so budget constraints affect the optimization model. Rehabilitation benefits consist of benefits from reduced repair costs and benefits from increased revenue due to reduced leakage in the rehabilitated pipelines. When the leakage rate is high, the pressure in the network drops and customer consumption decreases so that when the pipeline is rehabilitated, there will be benefits from increased revenue (customer consumption) due to increased pressure after reduced leakage. The development of this optimization model is needed to assist in optimizing the determination of rehabilitated pipelines for the reactive maintenance type.

The model for obtaining the main variables is obtained from the following references as shown in Table 5. Rehabilitation cost is modeled by Jayaram et al. (2008) in [12], Shin et al. (2016) in [13] and Ibrahim (2018) in [14]. Meanwhile, benefit from reduced repair costs is modeled by Jayaram et al. (2008) in [12], Shin et al. (2016) in [13], Mahmoodian et al. (2017) in [15], Ibrahim (2018) in [14] and Kim et al. (2019) in [9]. Benefit of increasing revenue due to reducing leaks is modeled by Kim et al. (2018) in [9].

Table 5 References to the model for calculating the costs and benefits of rehabilitation

Variable	References
Rehabilitation cost	Jayaram et al. (2008), Li (2013), Shin et al. (2016), Ibrahim (2018)
Benefit from reduced repair cost	Jayaram et al. (2008), Li (2013), Shin et al. (2016), Mahmoodian et al. (2017), Ibrahim (2018), Kim et al. (2019)
Benefit from increasing revenue due to leaks reduction	Kim et al. (2019)

The optimization model that is carried out is a model to get the maximum benefit/cost ratio. The optimization equation can be described as follows.

$$Z = \frac{F(X2) + F(X3)}{F(X1)} \tag{1}$$

Where Z is optimization value, F(X1) is the rehabilitation cost, F(X2) is the benefit of reduced repair costs, and F(X3) is the benefit of increasing revenue from reduced leakage. In the optimization model, there are limitations to the rehabilitation budget.

6 Conclusion

The existing methods are basically built from a rehabilitation approach to a proactive maintenance strategy by assuming there are no budget constraints. While the problems faced by many water distribution providers in Indonesia are generally due to budget constraints.

Based on this, it is necessary to apply a method based on a reactive maintenance strategy to overcome the problem of selecting pipes to be rehabilitated in water distribution pipelines in Indonesia. The method based on a reactive maintenance strategy is apart from budget constraints and the leakage rate is already very high. Thus, the proposed method must consider the economic and technical aspects simultaneously in a cost-benefit consideration.

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