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GROUP MAINTENANCE SCHEDULING: A CASE STUDY FOR A PIPELINE NETWORK

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This paper presents a group maintenance scheduling case study for a water distributed network. This water pipeline network presents the challenge of maintaining aging pipelines with the associated increases in annual maintenance costs. The case study focuses on developing an effective maintenance plan for the water utility. Current replacement planning is difficult as it needs to balance the replacement needs under limited budgets. A Maintenance Grouping Optimization (MGO) model based on a modified genetic algorithm was utilized to develop an optimum group maintenance schedule over a 20-year cycle. The adjacent geographical distribution of pipelines was used as a grouping criterion to control the searching space of the MGO model through a Judgment Matrix. Based on the optimum group maintenance schedule, the total cost was effectively reduced compared with the schedules without grouping maintenance jobs. This optimum result can be used as a guidance to optimize the current maintenance plan for the water utility.

Keywords: Group Maintenance Scheduling, Genetic Algorithm, Maintenance Grouping Optimization (MGO), Judgment Matrix, Water Pipeline

1. INTRODUCTION

Previously, a Maintenance Grouping Model has been proposed by the authors [1] to consider group scheduling for pipeline maintenance. This paper presents a case study for the application of this model in the maintenance scheduling of a water distribution network in Australia [1]. Some of the parts of the pipelines were aging which presented a challenge to the maintainers as the number of failures of these pipelines was rising over the years which cost millions of dollars to maintain annually. Pipelines can be maintained individually or in groups. This case study examines how these maintenance schedules can be grouped together to reduce total cost, and considers the balance between maintenance cost and reducing the number of failures in the network using life cycle cost analysis.

The paper reports on the benefits of a group maintenance scheduling program for a water distribution network based on a Maintenance Grouping Optimization model, which makes for an optimum solution for grouping maintenance schedules at targeted planning horizons over the next 20 years.

The paper begins with a literature review of the core theories and existing research relevant to pipeline maintenance decision planning in Section 2, followed by an introduction of the new model for group maintenance scheduling. An overview of the water pipeline network is introduced in Section 3. In Section 4, a 20-year group maintenance schedule is presented for the water pipeline network utilizing the new model introduced in Section 2. The analysis of the results is presented in Section 4. A summary of the work performed to date and a proposal for future work is presented in Section 5.

2. THEORY AND LITERATURE

Whether to replace or maintain a pipeline is an extremely significant and difficult decision for utility owners. A good maintenance decision is about maintaining the right pipe, at the right time and using the right maintenance strategy and technology. Literature on maintenance planning for water distributed network offers interesting approaches.

Based on a statistical analysis of pipe lifetimes, a software KANEW [2] was developed, which deals with system wide renewal decisions for different water main categories. This water mains replacement scheduling model can schedule replacement in any time intervals, with the expenditure in each period constrained by available funds. Engelhardt [3] developed a method by allowing the replacements to be scheduled over a 20 year period, which was split into four five-year time periods with the expenditure in each period constrained by available funds considering various time-dependent parameters, such as increases in demand. Sægrov presented a decision support system CARE-W [4], which allowed selecting and scheduling rehabilitation jobs taking into account deterioration. This software provided a hydraulic modeling to access pipeline reliability of the network. Based on risk calculation, PARMS-PRIORITY [5] was developed and contained failure prediction, cost assessment, data exploration and scenario evaluation.

A non-homogeneous Poisson model I-WARP [6] was used to model the probability of breakage in individual water pipelines. It allowed for the consideration of three classes of covariates, pipe-dependent, time-dependent and pipe and time dependent. A renewal scheduling model [7] was developed for water main renewal planning, which took into account life cycle costs and associated savings due to reduced mobilization costs by setting a contiguity discount. However, it only considers two pre-determined situations, ie, that two pipes share the same node and both are replaced in the same year.

Most of maintenance decision models in previous research only considered individual pipes. However, from the water utilities owner's point of view, group maintenance scheduling can certainly reduce the cost of replacement. In current practice, replacement planners usually have no choice but select two or three pipes manually with ambiguous criteria to group as one replacement job. This practice is not a viable solution for pipe grouping and is not cost effective. To address this issue, a novel concept of group maintenance scheduling was introduced by Li [1]. The proposed Maintenance Grouping Optimization (*MGO*) model was shown to assist distributed pipeline assets owners and operators to make group scheduling decisions for replacement of water pipelines. They created a Judgment Matrix considering three grouping criteria (adjacent geographically distribution, identical replacement machinery and similar service interruption areas). This Judgment Matrix corresponded to various combinations of pipe replacement schedules. A modified cost model was developed to calculate the total cost of each pipeline at each year. A modified Genetic Algorithm model was proposed to deal with the scalability of the vast combinatorial solution space for finding the optimum group maintenance scheduling option, with the objective of minimizing total cost.

This case study started from three cost models and adopted the Non-homogeneous Poisson based model to predict the probability of breakages and the per-analysis (calculating the total cost) to filter the pipes that will not be replaced during the 20-year planning horizon. The proposed group maintenance scheduling model was subsequently utilized with one of the three grouping criteria (adjacent geographically distributed) to find the optimum maintenance schedule. The influences of customer interruption of the group maintenance schedule were not included in this work.

3. OVERVIEW OF THE PIPELINE NETWORK

3.1 Overview of the Water Distributed Network

This water distributed network services a community in Australia, and comprises *66,405* pipes (total length of *3,640*km, at an average length of pipe of *54.79*m), with diameters from *20mm* to *1440mm*, in *11* different materials, installed between 1937 and 2010. It services a population of nearly *50,000* inhabitants through *9* different workstations. An overview of the network is presented in Table 1.

Table 1. Overview of the Water Distributed Network

Item	Description
Pipe's Diameter	20mm, 32mm, 40mm, 45mm, 50mm, 63mm, 75mm, 80mm, 90mm, 100mm, 110mm, 150mm, 200mm, 220mm, 250mm, 300mm, 375mm, 411mm, 450mm, 500mm, 510mm, 525mm, 565mm, 590mm, 600mm, 660mm, 700mm, 750mm, 800mm, 850mm, 900mm, 915mm, 960mm, 965mm, 1050mm, 1125mm, 1290mm, 1440mm
Pipe's Material (*11* types)	Asbestos Cement(AC), Cast Iron Cement Lined(CICL), Concrete(CONC), Copper(CU), Fibre Reinforced Pipe(FRR), Galvanised Steel(GAL), Glass Reinforced Plastic(GRP), Glass Reinforced Plastic(HOBAS), Ductile Iron Cement Lined(DICL), Mild Steel Concrete Lined(MSCL), Unplasticised Poly Vinyl Chloride(UPVC)
Pipe's Length	From 0.1m to 1363.9m
Zone area types	RURAL (RUR), URBAN (URB), HIGH DENSITY URBAN (HDU), CBD
Population	*515,157* * People

* Based on projected figures. Source: PIFU; ABS, Regional Population Growth, Australia, 2006-2007

3.2 Age Profile of the Water Pipeline Network

The oldest water pipes in the network dates back to 1937. Around *102km* of the total length of pipes now in operation were installed before 1960. Almost all pipes were made from concrete or cement before 1960. The years 1961 to 1990, saw a significant increase in installations, and nearly half of the total number of pipes (3/5 of total length) were constructed in this period. The most commonly used materials were ductile iron, grey cast iron and mild steel. In 1960, the first PVC pipes were constructed and have become the preferred material for replacements and expansions after 1970s.

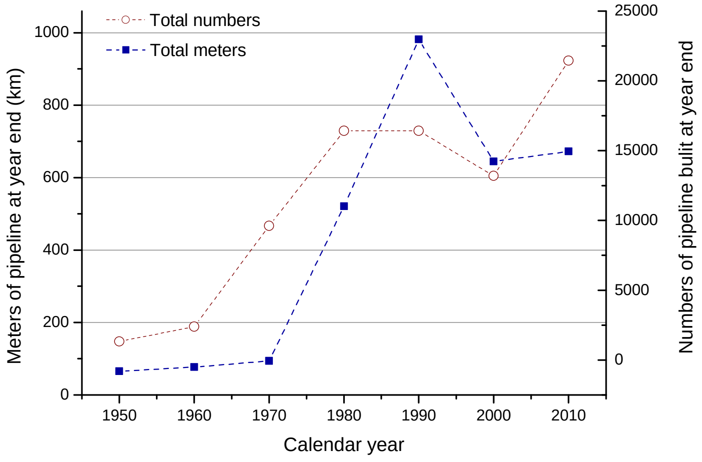


Figure 1: Construction History

The average age of the whole network is 21 years, but the age of *1,356* pipes (2% of total network) exceed 60 years, ie, *70*km in total.

3.4 Pipeline Repair History

The water company recorded *3,128* pipe repairs during 2000 to 2010, with the structure of the work order as follows: pipe ID, depth (>1.5m and <1.5m), repair start and finish date and time, and repair cost. Naturally some of these data were found to be missing for various reasons while *2,526* sets of valid data were filtered for analysis. Over 10 years, the water company conducted *3,823* repair jobs for unexpected breaks, which means several pipes broke twice or more, and cost *AUD$4* million. Figure 3 shows that the repair cost correlated with the number of breaks which rose from 2000 to 2010, and decreased slightly in 2005, and then peaked at *AU$0.86* million in 2010. The drop in the number of breaks in 2005 remains unexplained and is being analysed further at this time.

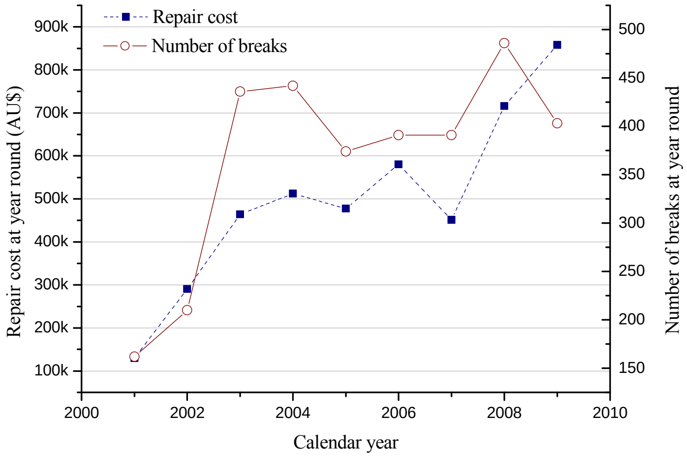
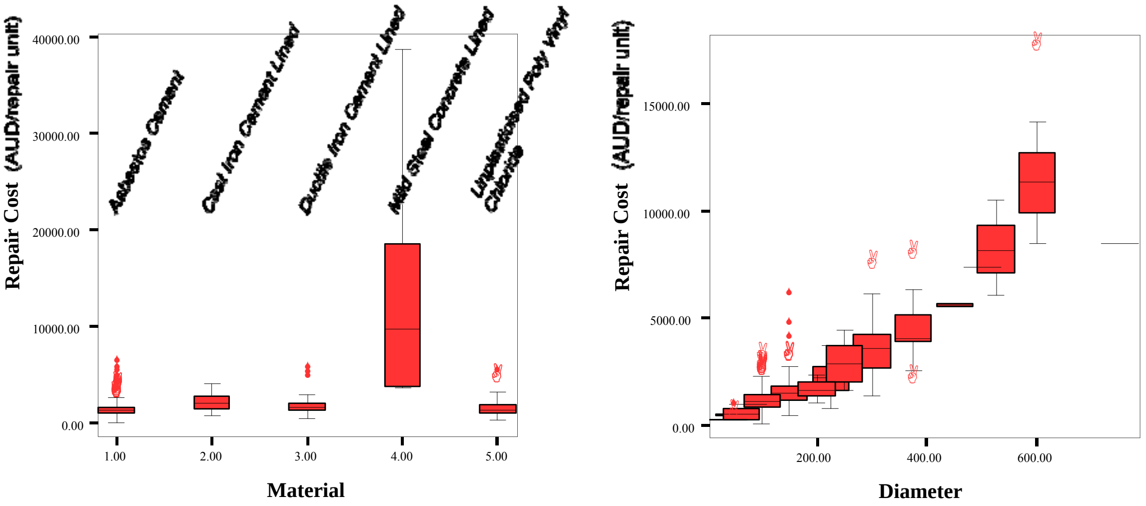


Figure 2: Repair History from 2000 to 2010

The *2,526* records of pipeline repair corresponded to five different pipe materials, which were Asbestos Cement (AC), Cast Iron Cement Lined (CICL), Ductile Iron Cement Lined (DICL), Mild Steel Concrete Lined (MSCL), and Unplasticised Poly Vinyl Chloride (UPVC). These pipes were installed from 1937 to 1990, and were generally near their end of life (60-80 years). A statistical analysis was conducted to analyse the relationships between the repair cost and materials as well as repair cost and diameter. Two box and whisker plots are illustrated in Figure 4 to show different materials and diameters of repair cost data through the smallest cost, lower quartile, mean value, upper quartile, and the largest cost observation. Figure 3 (a) illustrates that the repair cost shows dramatic differences between MSCL and the other materials. Three reasons caused the high price of MSCL pipes' repair cost: 1) the price of this material on its own was extremely higher than the other materials; 2) the repair method and procedure utilized in MSCL pipes were more complicated that the other pipes; 3) larger diameters were used in the MSCL pipes (>300mm). Moreover, the other materials showed a similar repair cost in this case, so that one can treat these four materials as a group, when the impact of material is taken into account.



(a) Repair Cost with Different Materials (b) Repair Cost with Different Diameters

Figure 3: Repair Cost with Different Materials and Diameters

Figure 3 (b) shows that the repair cost increased with the increase in diameter as shown in [8, 9]. Based on the repair data in this case, the relationship between the increase in the repair cost and pipe diameter was found to be nonlinear.

4. GROUP MAINTENANCE SCHEDULING

4.1 Repair Cost

Based on the *2,526* records of pipeline repair data, a regression model [10] was used and trained to calculate repair cost of each pipe i, based on the equation (1):

$$C_i^{rep} = a + b \cdot D_i^c + d \cdot u_i^e + f \cdot D_i \cdot u_i \qquad (1)$$

Table 2. Parameters for Repair Cost Equation

Material of pipe	***a***	***b***	***c***	***d***	***e***	***R^2***
AC, CICL, DICL, UPVC	*877.201*	*0.066*	*1.849*	*0.233*	*-0.146*	*0.99*
MSCL	*659.143*	*0.023*	*2.063*	*-0.002*	*19.399*	*0.89*

D_i indicates the diameter of each pipe i, and the decision variable u_i is the depth of the pipe buried, where "1" indicates the depth <= 1.5 meters, and "2" indicates the depth > 1.5 meters. $a, b, c, d, e,$ and f are coefficients, which are estimated by using the regression model. In this case, u_i is independent of D_i, therefore, parameter f is equal to 0. The coefficients of the repair cost equation with five different materials of pipes are given in Table 2.

4.2 Replacement Cost

Replacement costs are affected by the length, diameter, replacement technology and location of each pipe. The replacement cost function of each pipe i, C_i^{repl}, [1], is shown in equation (2), which contains three components, the cost related to length Cr_i, the machinery cost M_i and the travel cost Cv_i:

$$C_i^{repl} = \frac{M}{\sum\limits_{\forall i\in U} l_i} \cdot l_i + \frac{l_i \cdot \sum\limits_{\forall i\in U} \left(Cr_i \cdot l_i\right)}{\sum\limits_{\forall i\in U} l_i} + CV \frac{d_i^{\,2}}{\sum\limits_{\forall i\in U} d_i} \qquad (2)$$

where pipe i belongs to group U, d_i is the travel distance from work station to pipe i. The length related cost Cr_i is correlated to various diameters and materials, which shows in Table 3. The information in Table 3 is based on the historical contract payments for the last year for water main replacements.

Table 3. Water Pipes Replacement Cost (Cr_i)

Diameter (mm)	**Substituted Material**	Cr_i **(AU$/m)**	**Diameter (mm)**	**Substituted Material**	Cr_i **(AU$/m)**
90	PVC	$98	900	DICL	$2,575
100	PVC	$104	960	MSCL	$2,901
150	PVC	$168	1000	MSCL	$3,046
200	PVC	$229	1050	MSCL	$3,152
225	PVC	$254	1085	MSCL	$3,326
250	PVC	$273	1200	MSCL	$3,748
300	DICL	$461	1290	MSCL	$4,007
375	DICL	$654	1350	MSCL	$4,350
450	DICL	$777	1500	MSCL	$4,769
500	DICL	$946	1650	MSCL	$5,316
525	DICL	$1,020	1800	MSCL	$5,765
600	DICL	$1,240	1950	MSCL	$6,324
750	DICL	$1,759	2159	MSCL	$6,792

The factors affecting machinery cost remain unexplained in the current research. Therefore, it was assumed that the machinery cost is generally affected by the materials. Considering the analysis of repair cost, the results showed dramatic differences between MSCL and other materials. According to the case study made by Li, and considering the dramatic differences of the repair cost between the results of the MSCL and the other materials, the machinery cost was taken as *M=AUD$4,000/unit* for MSCL and *M=AUD$2,000/unit* for other materials. The *CV* is distance-unit cost, which is a constant value, and is set at *AUD$100/km* in this case.

4.3 Total Cost

The total cost C^{tot} associated with pipe replacement is affected by the replacement cost C_i^{repl} and pipeline failures [7]. The cost of pipeline failure includes two parts, 1) direct cost, which contains repair cost C^{rep}, direct damage cost C^{dir} and water loss cost C^{wat}, and 2) indirect cost, which comprises indirect damage cost C^{indir}, customer service interruption cost C^{inp} and social cost C^{soc}. In the current case, the authors considered the repair cost as an only component of failure cost, for it was impossible to calculate damage cost, water loss cost, customer service interruption cost and social cost. Therefore, the present value of the total cost associated with pipe *i* replaced at year *t* is given by:

$$C_{i,t}^{tot} = C_i^{repl} \big/ (1+r)^t + \sum_{p=1}^{t} k_{i,p}[C_i^{rep} \cdot \frac{1}{(1+r)^p}] \tag{3}$$

Where r is a discount rate which is equal to *“0.02”*, and $k_{i,p}$ is the probability of breakage in p^{th} year.

4.4 The Objective Function

The objective, in this case, is to minimize the present value of total cost of water distribution network. This took the group maintenance scheduling of candidate pipes into account during the *T* (*20*-year) planning horizon. The minimum total cost of the network during horizon T, C_{sys}^{tot}, is equal to the minimum cost of sum of the total cost of each pipe *i* in the selected t^{th} year, $t \in (1,2,\dots,T)$:

$$Min \quad C_{sys}^{tot} = Min \sum_{\forall t \in T} \sum_{i}^{N} C_{i,t}^{tot} \tag{4}$$

Constraints

1. The total cost of the pipes replacement in the planning horizon *T* years must be less than the total budget B_T

$$\sum_{\forall t \in T} \sum_{i}^{N} C_{i,t}^{tot} \le B_T \tag{5}$$

,

where, the annual budget of the whole water distribution network for replacement was *AUD$2* million. Therefore, the total budget of the whole water distributed network for replacement B_T is equal to $B_t \times T$, which was *AUD$40* million for 20 years.

2. For all grouping options, the distance from pipe *i* to pipe *j* must be equal or smaller than the maximum distance, which can be set by users.

4.5 NHPP Analysis

An analysis of forecast failure probability was conducted to screen the target pipes from the all pipes (*66,405* pipes). A well proved non homogeneous Poisson-based model [6], which is capable of considering time-dependent covariates, was used to forecast the probability of breakages. It was assumed that the breaks at year *t* for an individual pipe *i* satisfied Poisson process with mean intensity $\lambda_{i,t}$. The probability of breakages $k_{i,t}$ is given by:

$$P(k_{i,t}) = \frac{\lambda_{i,t}^{k_{i,t}} \cdot e^{-\lambda_{i,t}}}{k_{i,t}!} \tag{6}$$

$$\lambda_{i,t} = \exp\left[\alpha_0 + \theta \log\left(g_{i,t}\right) + \alpha \log\left(z^i\right) + \gamma q^{i,t}\right] \tag{7}$$

Where $g_{i,t}$ is the age of pipe *i* at year *t*, z^i is the length of pipe *i*, and $q^{i,t}$ is the number of known previous failure breaks. α_0, θ, α, and γ are coefficients. The *2,526* records of pipe repairs were used for training the model to find the four coefficients, which are shown in Table 4.

Table 4. Coefficients of NHPP Model

Covariate	α_0	θ	α	γ
Coefficient	-3.846	0.54	0.75	0.32

The forecasted failure probabilities of each pipe *i* at each year *t* were calculated by using the prediction model. The forecasted failure probabilities of selected seven pipes over 20-year planning are shown in Figure 4. Figure 5 illustrates the relationship between the failure probabilities and the number of pipes. Almost *80%* of total pipes' failure probabilities were lower than *0.1*, and only a few pipes' failure probabilities were higher than *0.1*.

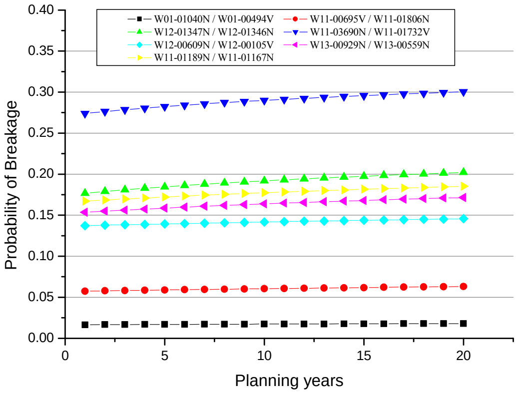


Figure 4: Sample of Forecasted Failure Probability

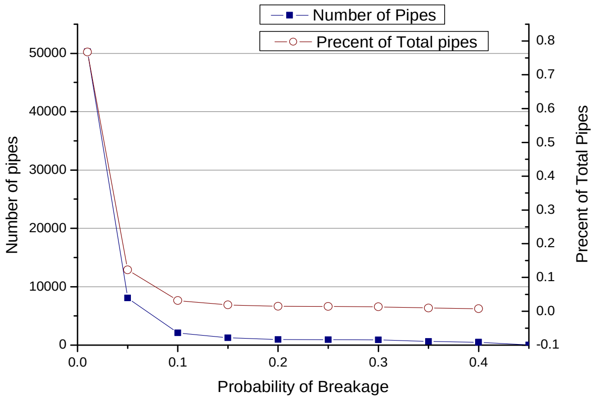


Figure 5 Distribution of the Failure Probability with Pipe numbers

To increase the computing efficiency, only the pipes whose forecasted failure probabilities were higher than *0.1* were considered for further analysis. If the failure probability of one pipe is lower than *0.1, which* indicates that this pipe was unlikely to fail in the future years, then this pipe do not need to replace. According to this criterion, , *7,191* (*23%*) pipes were selected for the further analysis.

4.6 Pre-analysis

Based on Equations (1-5), the total cost of each pipe *i* at each selected year *t* was calculated, without considering group maintenance schedules. *1,092* pipes were selected from the *7,191* pipes with high failure probabilities, whose minimum cost happened within the decision horizon *T=20*.

Table 5. Summary of the Selected Pipes

Item	**Description**
Diameter	40mm, 50mm, 63mm, 100mm, 150mm, 200mm, 220mm, 300mm, 375mm, 450mm, 500mm, 525mm, , 600mm, 660mm, 750mm, 850mm, 960mm, 965mm
Material (5 types)	Asbestos Cement(AC), Cast Iron Cement Lined(CICL), Concrete(CONC), Ductile Iron Cement Lined(DICL), Mild Steel Concrete Lined(MSCL)
Length	From 2.1m to 1,843m

4.7 Judgment Matrix

Judgment Matrix was calculated using the following equations [1],

$$\Lambda = \begin{bmatrix} \varepsilon_{11} & \cdots & \varepsilon_{1j} & \cdots & \varepsilon_{1n} \\ \vdots & \ddots & \vdots & & \vdots \\ \varepsilon_{i1} & \cdots & \varepsilon_{ij} & \cdots & \varepsilon_{in} \\ \vdots & & \vdots & \ddots & \vdots \\ \varepsilon_{n1} & \cdots & \varepsilon_{nj} & \cdots & \varepsilon_{nn} \end{bmatrix}, \tag{8}$$

where $\mathcal{E}_{ij} = \begin{cases} \gamma_{ij}, & \gamma_{ij} \le \gamma^* \\ 0, & \text{otherwise} \end{cases}$, γ_{ij}= Geographic distance from pipe i to pipe j (km), and γ^*= Maximum geographic distance (km), $i, j, n \in N$, i, j, n are the indexes of pipes, and N is the total number of pipes in the network.

The maximum geographic distance γ^* is an input value, which can be determined by users. In this case, the maximum geographic distance γ^* was determined through calculating the distance between the nine workstations. The minimum distance among the nine workstations was equal to *4.3km*. It was assumed that one replacement job can only be done by only one work team from only one workstation. Therefore, the maximum geographic distance γ^* was equal to the half of the minimum distance among the nine workstations, which means γ^* was equal to *2.15km*.

The judgment matrix in this case was a "*1092 by 1092*" matrix with the rational numbers from *"0"* to *"2.15km"*. Figure 6 shows the judgment matrix, the *black* colour indicates that the distance was beyond the *"2.15km", which* means that there was no grouping pipes with corresponding pipes, the colours from *"white"* to *"gray"* means the distance from *"0"* to *"2.15km"*.

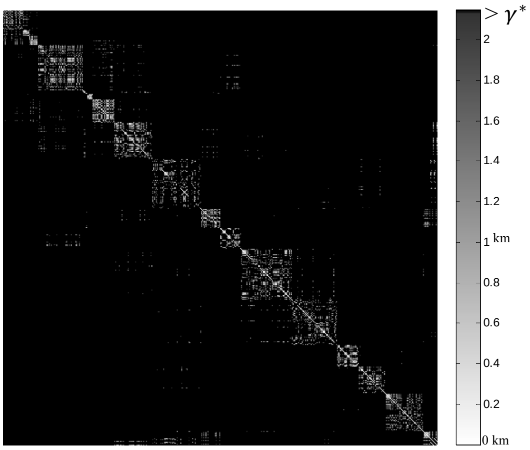


Figure 6: Judgment Matrix

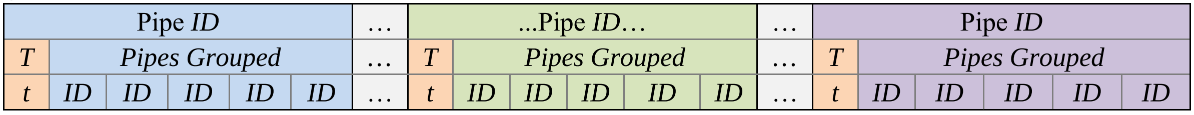
4.8 Group Maintenance Scheduling

For group maintenance scheduling, the Grouping model presented in [1] was utilized to analyse the different grouping options. The Grouping model was based on a modified Genetic Algorithm (GA) model, and the parameters of that GA model was listed in Table 6.

Table 6. Parameters of the Modified GA Model

Number of individuals	300	Generation gap	0.9
Maximum generations	500	Maximum number of pipes grouped	5

The working time of one replacement job is depends on many factors, ie, pipe's length, location, diameter, material and working efficiency of work team. Practically, one replacement job at least takes *4* hours, therefore, we assumed that one group of jobs is not longer than *3* working days, which means that the maximum number of pipes in one groupe does not exceed five. According to the structure of the modified GA model, the genes number was decided by the maximum number of pipes in one group. Therefore, in this case study, the representation involved *6* 'genes' for each pipe of the network, which shows in Figure 7. Therefore, one chromosome had *6,552 (1,092 ×6)* genes.



Pipe *ID*						…	...Pipe *ID*…						…	Pipe *ID*					
T	*Pipes Grouped*					…	*T*	*Pipes Grouped*					…	*T*	*Pipes Grouped*				
t	*ID*	*ID*	*ID*	*ID*	*ID*	…	*t*	*ID*	*ID*	*ID*	*ID*	*ID*	…	*t*	*ID*	*ID*	*ID*	*ID*	*ID*

Figure 7 Chromosome representation

4.8 Results and Discussion

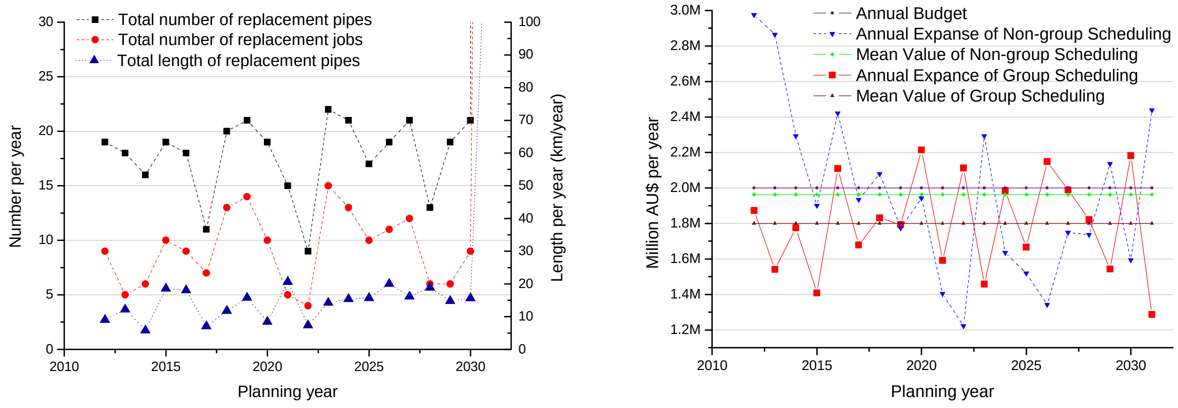
Using the MGO model, an optimum group maintenance schedule was planned for the planning horizon.

An example of first year planning is listed in Table 7. In the first year, *19* pipes will be replaced in 9 grouped replacement jobs. The total pipe lengths in each job will be smaller than *2km*, which was assumed to be the maximum replacement length of one job.

Table 7. Example of the first year planning

Job	Pipeline	Total Length
1	W01-00265N / W01-01704N W01-01414N / W01-00154V	*1,317m*
2	W01-00820V / W01-01058V	*357m*
3	W01-00272V / W01-00274V W02-00195N / W02-00174V W04-00592N / W04-00697V	*1,677m*
4	W04-00302N / W04-00551V W04-00588N / W04-01795N W10-01237N / W10-00434V W10-01502N / W10-00888N	*1,606m*
5	W10-00465N / W10-00649V W13-00607V / W13-00608V	*792m*
6	W07-00652V / W07-00648V W10-00467V / W10-02169N W10-01847N / W10-00446V	*1,815m*
7	W10-01448N / W05-00074V W12-00098V / W12-00094V	*810m*
8	W15-00113V / W15-00110V	*291m*
9	W12-01377N / W12-01382N	*369m*

Figure 9(a) shows the number of pipes planned to replace, the number of replacement jobs and the total length of pipes planned to replace for the next *20* years. From the values in each year, it is noticed that there are significant differences among total number and total length of pipes replacement for each planning year, which breaks the convention that the total numbers and lengths of replacement pipes should slightly increase annually. Actually, the planning replacement jobs fluctuated during the planning horizon, and there was no clear regularity showed in the optimum replacement planning.



(a) Number and length

(b) Comparison of Annual expanse and budget

Figure 9 Statistical Information of the Group Scheduling

In Figure 9(b), the situation of replacement planning with considering group scheduling or not is compared. The annual expenses for both grouped and non-grouped scheduling are changed grammatically each year. The annual expenses of five different years for grouped scheduling is a little higher than the annual budget (*AUD$2* million). On the contrary, the annual expenses of eight different years for non-grouped scheduling is higher than annual budget, especially in the first two years. The mean value for the total expenses of *20* years for the non-grouped scheduling is *AUD$1.96* million each year, which is just below the budget. The mean value for the total expenses for the group scheduling is *AUD$1.8* million each year, which has *AUD$0.2* million and *AUD$0.14* million cost saving compared with the annual budget and the non-grouped scheduling respectively. The total cost for the 20 years non-grouped scheduling is around *AUD$39* million. On the contrary, the total cost for the 20 years group scheduling is around *AUD$36* million, which is *AU$4* million (*10%*) and *AU$3* million (*7.5%*) cost reduction for the 20 planning years.

5. CONCLUSIONS

Optimum maintenance schedules are desirable for owners and operators of water pipeline networks to balance maintenance cost and the degradation of the network. To reduce total cost, maintenance schedules can be conducted in groups of pipes rather than individually. This paper validates that the Maintenance Grouping Optimization model based on a modified genetic algorithm is a good optimization model for techniques for managing pipeline maintenance, through developing an optimum group maintenance schedule for a water pipeline network over a 20-year cycle. The adjacent geographical distribution of pipelines can be used as a grouping criterion to control the searching space of the MGO model through a Judgment Matrix. Based on the optimum group maintenance schedule, the total cost can effectively come down compared with the schedules without grouping maintenance jobs. This model is a good technique for optimizing the current maintenance planning for the water utility.

Potential MGO model applied for other types of distributed assets including electricity distribution networks, railway networks and road networks will be tested in the future research.

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