Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2017.21285

96 (2017) 211–218
November

Developing LCC and risk analysis method for dewatering facility based on its management history

Youngwook Nam, Jihoon Choi, Dooil Kim*

Department of Civil and Environmental Engineering, Dankook University, 152 Jukjeon-ro, Suji-gu, Yongin-si, Gyeonggi-do 16890, Korea, email: dikim21@dankook.ac.kr (D. Kim)

Received 1 March 2017; Accepted 3 August 2017

ABSTRACT

Operation and management of wastewater treatment facilities are critical for facility owners because of limited budget and aging equipments. The assets in a facility are huge in number and amount and complicated, which make owners to adopt an asset management system to their facility. In this research, we compared proactive management cost (PMC) and follow-up management cost (FMC) using life cycle cost (LCC) and risk management, which were major part of asset management for the wastewater treatment plant located in South Korea. For this, we developed a method to forecast future maintenance cost of a dewatering facility in a wastewater treatment plant. We also developed a method to obtain average occurrence probability and average occurrence cost using data grouping method with equal width of the valid data of USD 273.0. And then, we predicted cumulated maintenance cost (CMC) and cumulative distribution function (CDF). LCC results of dewatering facility were obtained from maintenance cost data and Bernoulli trials. It was expected that the maintenance cost reaches $234,778 after 385 months from its installation. We calculated value at risk (VaR) using average occurrence probability and repair cost. We calculated PMC and FMC using VaR and LCC. Proactive maintenance was beneficial to facility owners because the maximum difference at 285 months between PMC and FMC was USD 37,530.

Keywords: Wastewater treatment plant; Dewatering facility; Asset management; Life cycle cost; Risk management; Value at risk; Proactive management

1. Introduction

Operation and management of water treatment facilities are critical for facility owners because of limited budget and aging equipments. Deciding optimal time slot for equipment repair or replacement for a water treatment facility is trouble of facility owners. In addition, to replace with new equipment lays economic burden to facility owners, which makes us manage aged equipment more efficiently to extend their life in a facility [1]. The assets in a water treatment facility consist of land, building, machine, electrical equipment, and instruments, including every consumable in the facility [2]. The operational cost of maintaining these assets is proportional to the size of the assets in a facility [3]. The assets in a facility are huge in number and amount and complicated, which makes owners to adopt a scientific and systematic method to handle them. An asset management was evolved to cope with these necessities [4].

Asset management of a facility differs from an inventory management, which has been traditionally used. Inventory management focus on keeping records on the amount of assets left in a facility [4]. It is hard for a facility owner to predict future needs and do proactive repair or maintenance because inventory management system is follow-up management. In the contrary, the asset management has started to do proactive management of a facility. Proactive maintenance is beneficial to both a facility owner and water consumers

* Corresponding author.

Presented at the 9th International Conference on Challenges in Environmental Science & Engineering (CESE-2016), 6–10 November 2016, Kaohsiung, Taiwan.

because this method can save maintenance cost and sufferings from service interruption. The asset management method was first developed in the field of business administration and later adopted in the management of social infrastructure including road, facility, and building.

Every equipment and part in water treatment facility has its useful life [5]. The useful life could be extended by efficient maintenance, including repeated repairing equipments or replacing parts. When life span of equipment is over or in critical state, facility owners need to decide whether to replace or repair their aged equipment. Facility owners need to choose best options among spending money for repairing aged equipment and replacing it. This is why life cycle cost (LCC) analysis is important to facility owners. LCC is a price spent through all its life, which is the cost spent from its purchase to disposal [6]. The whole cost is recorded and called historical data [7]. The historical data are used to support the owner to make critical decision on asset management [8]. Generally, LCC is defined to be long-term cost occurred for infrastructure planning, design, construction, and operation [9]. The importance of LCC analysis has increased as proactive maintenance becomes more significant than reactive maintenance [9]. Reactive maintenance is a follow-up maintenance to repair equipment or replace parts after it is broken. On the contrary, proactive maintenance is managing equipment based on systematic schedule before out of order. It is similar to replace automotive engine oil before an engine is broken. Proactive maintenance of engine oil is an efficient method because it can prevent unexpected breakage and thus save follow-up cost and extend the life span of a car.

For proactive asset management, it is required to predict the optimal time slot to replace parts or repair equipment from analysis of historical data of maintenance. Therefore, it is necessary to provide a rational method for facility owners to decide proactive action time. Proactive maintenance is also critical for uninterrupted water supply service system. In addition, proactive maintenance is more economical than follow-up method. The objectives of this research are to forecast future maintenance cost of a wastewater treatment plant and then compare the costs for proactive and reactive maintenance after deciding optimal maintenance time slot.

2. Model development

2.1. The wastewater treatment plant

The wastewater treatment plant is located in South Korea and has capacity of 80,000 m^3/d. Average daily flow rate is 61,000 m^3/d. The process consists of primary sedimentation, aerobic treatment, and secondary sedimentation. The sludge is treated by anaerobic digestion, followed by mechanical decanter for concentration and dewatering. The dewatered sludge is disposed at a landfill. Fig. 1 shows the schematic diagram of the wastewater treatment plant.

2.2. Collecting maintenance history data

All the maintenance history of dewatering facility occurred during operation has been recorded on the log book or an asset management system [10]. For this research, the LCC analysis was carried out for dewatering facility since it has abundance for accumulated maintenance data [11]. The maintenance history is summarized at Table 1. The data were collected during 40 months from September 2011 to December 2014.

2.3. Predicting historical data using a Bernoulli sequence

The recurrence time in a Bernoulli sequence is controlled by the geometric distribution. The mean recurrence time is return period and defined in Eq. (1):

$$\bar{T} = E(T) = \Sigma_{t=1}^{\infty} t \cdot pq^{t-1} = p\left(1 + 2q + 3q^2 + \ldots\right) \quad (1)$$

where $\bar{T}$, average return period; T, the actual time; $E(T)$, event in time; t, time; p, occurrence probability; q, no occurrence probability.

Since $q = (1 - p) < 1.0$, the infinite series within Eq. (1) yields $1(1 - q)^2 = 1/p^2 < 1.0$. In addition, the mean recurrence time between two successive events is equal to the reciprocal of the probability of the event within one time interval. The actual time is T, which is a random variable [12].

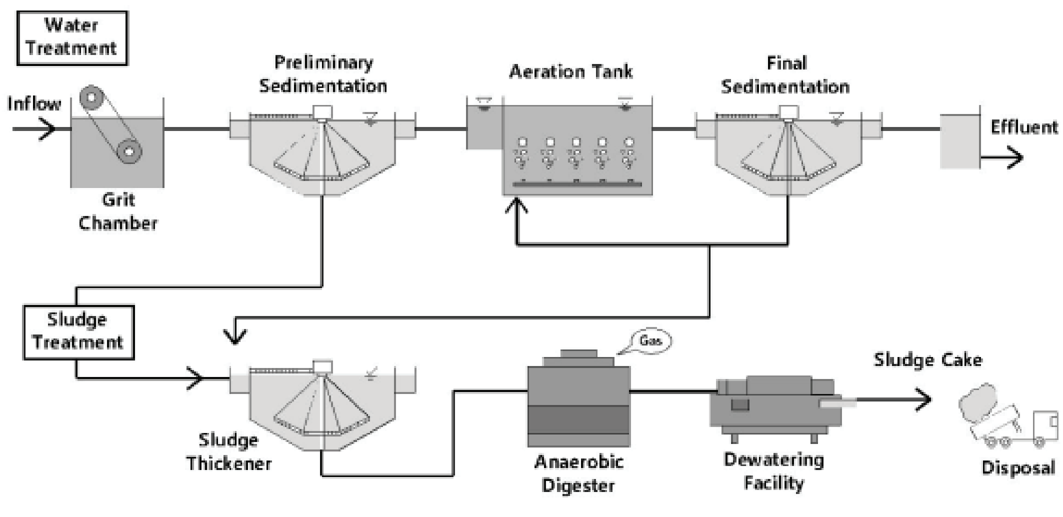

Fig. 1. Schematic diagram of water and sludge treatment in the plant.

Table 1
Maintenance history data of the equipment (1 USD: 1,100 KRW)

Time (month/year)	Historical data	Cost (USD)
09/2011	Sewage sludge cake roller box repair	$636
09/2011	Sewage sludge cake roller box repair	$455
09/2011	Dewatering facility cake conveyor scraper replacement	$45
11/2011	Sludge supply pump universal joint replacement	$318
12/2011	Dewatering facility cake conveyor reducer repair	$818
12/2011	Sewage sludge cake roller box repair	$164
12/2011	Dewatering facility cake conveyor roller replacement	$1,118
01/2012	Cake roller box repair	$327
01/2012	Dewatering facility cake conveyor chain replacement	$824
02/2012	Sludge supply pump packing replacement	$55
02/2012	Quantitative feeder cylinder and funnel purchase	$123
⋮	⋮	⋮
01/2014	Sludge supply pump rotor and stator replacement	$818
01/2014	Two cake roller box roller replacement	$327
01/2014	Cake roller box ring welding and repair	$27
03/2014	Cake roller box handle and ring repair	$100
03/2014	Sewage sludge cake roller box repair	$45
08/2014	Dewatering facility cake conveyor reducer repair	$1,273
08/2014	Dewatering facility cake conveyor roller replacement	$1,118
09/2014	Dewatering facility cake conveyor replacement	$110
11/2014	Sewage sludge cake roller box repair	$600
12/2014	Sewage sludge cake roller box pipe repair	$136

The probability of no event occurring within its return period $\bar{T}$ is defined as Eq. (2):

$$P\left(\text{no occurrence in } \bar{T}\right) = (1-p)^{\bar{T}} \tag{2}$$

where $p = 1/\bar{T}$.

We could expand the above with the binomial theorem as Eq. (3):

$$(1-p)^{\bar{T}} = 1 - \bar{T}p + \frac{\bar{T}\left(\bar{T}-1\right)}{2!}p^2 - \frac{\bar{T}\left(\bar{T}-1\right)\left(\bar{T}-2\right)}{3!}p^3 + \cdots \tag{3}$$

Furthermore, for large $\bar{T}$ or small p, the series on the right side is approximately equal to $e^{-\bar{T}p}$ [12]. Therefore, for large $\bar{T}$, we can express like Eqs. (4) and (5):

$$P\left(\text{no occurrence in } \bar{T}\right) = e^{-\bar{T}p} = e^{-1} = 0.3679 \tag{4}$$

$$P\left(\text{occurrence in } \bar{T}\right) = 1 - 0.3679 = 0.6321 \tag{5}$$

For Bernoulli trial, average occurrence probability ($\bar{P}$) is renewed by cumulative distribution function (CDF) of 0.6321, which is the time slot for repair. After this, CDF returns to zero. The maintenance is mathematically simulated using the CDF values. Table 2 shows the occurrence probability, CDF, and its formula.

2.4. Risk calculation from maximum value at risk

Accidents in the future tend to have unpredictability and uncertainty [13]. Risk was defined to be future uncertainty which could be quantified. If uncertainty could not be quantified, it was called ambiguity [13]. For management, we need to understand risk to make more profit through risk or to keep away from loss by avoiding risk [14]. To reduce the operational cost, we need to calculate future quantitative risk by diagnosis of the equipment [10]. We used the concept of value at risk (VaR) that has been used by an insurance company or an investment bank. The VaR is also conceptually illustrated in Fig. 2. They need to calculate this value to prepare sudden bankrupt of a company which they invested [13]. VaR is mathematically defined as sum of mean risk and multiplied error as Eq. (6):

$$\text{VaR} = \mu + k\sigma \tag{6}$$

where μ, mean risk; k, multiplier; σ, error.

A multiplier of standard deviation varies according to the target confidence level. If we set confidence level to be 1%, 5%, and 10%, the multiplier is 2.33, 1.65, and 1.29, respectively [13].

Table 2
Representative example of Bernoulli trials for section 2 of Fig. 6

Operating time (month)	Occurrence probability	Cumulative distribution function	Occurrence cost (USD)	$p = 1/\bar{T}$	$q = (1-p)$	Occurrence cost (USD)
				0.1750	0.8250	$322
				Occurrence probability formula		
$n = 1$	0.1750	0.1750	–	$P(N = 1) = p \cdot q^0 = p = 0.1750$		
$n = 2$	0.1444	0.3194	–	$P(N = 2) = p \cdot q^1 = 0.1750 \cdot 0.8250$		
$n = 3$	0.1191	0.4385	–	$P(N = 3) = p \cdot q^2 = 0.1750 \cdot 0.8250^2$		
$n = 4$	0.0983	0.5367	–	$P(N = 4) = p \cdot q^3 = 0.1750 \cdot 0.8250^3$		
$n = 5$	0.0811	0.6178	–	$P(N = 5) = p \cdot q^4 = 0.1750 \cdot 0.8250^4$		
$n = 6$	0.0669	0.1750	$322	$P(N = 6) = p \cdot q^5 = 0.1750 \cdot 0.8250^5$		
$n = 7$	0.0552	0.3194	–	$P(N = 7) = p \cdot q^6 = 0.1750 \cdot 0.8250^6$		
$n = 8$	0.0455	0.4385	–	$P(N = 8) = p \cdot q^7 = 0.1750 \cdot 0.8250^7$		
$n = 9$	0.0376	0.5367	–	$P(N = 9) = p \cdot q^8 = 0.1750 \cdot 0.8250^8$		
$n = 10$	0.0310	0.6178	–	$P(N = 10) = p \cdot q^9 = 0.1750 \cdot 0.8250^9$		
$n = 11$	0.0256	0.1750	$322	$P(N = 11) = p \cdot q^{10} = 0.1750 \cdot 0.8250^{10}$		
⋮	⋮	⋮	⋮	⋮		

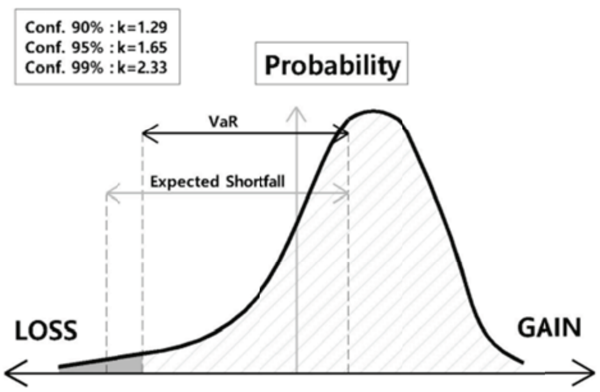

Fig. 2. Schematic diagram of the concept of VaR.

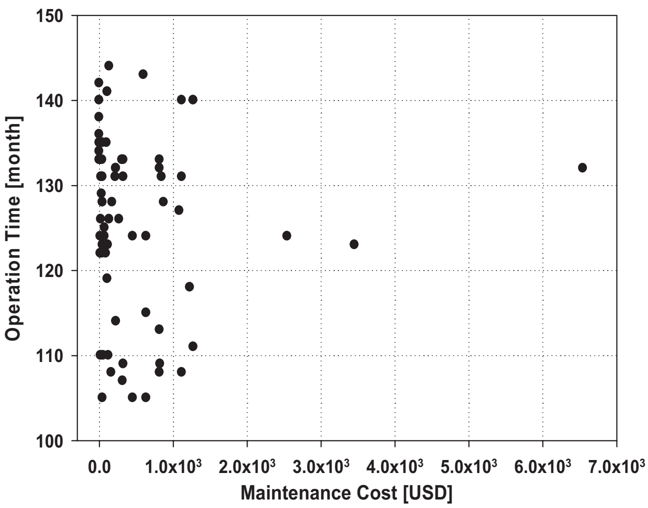

Fig. 3. Maintenance cost (x) vs. operation time (y) of the facility.

3. Results and discussion

3.1. Processing historical repair data

Fig. 3 shows major or minor maintenance cost over operation time until 145 months after the beginning of the operation of the plant. Since these data are randomly distributed, it is hard to find useful data from this. First, we tried to classify the random data according to the major parts to which the data belong as shown Table 3. If the major part was similar, the cost was also comparable from Table 3. We could find the trend from this table using repair cost and decided to use it as critical parameter to classify maintenance data. We can visually find that the data could be separated at the point with $1,400 in the x axis as shown in Fig. 4. We magnified the shaded part of Fig. 4 in Fig. 5 and then divided the data within $1,400 into five sections, which is one of the discrete methods among many data mining technique. The repair and replacement cost were representative class information for this research [10]. For the simplicity and generality of the model, we used equal width method. Since equal width method is arbitrary according to section width which enormously affect on the final results [10], we compared four scenarios according to equal width using standard deviation and valid data number of the Gaussian distribution as shown in Table 4. When equal width was USD 364.0, it was improper since we have four sections with the valid data of 34 as shown in Table 4. In the contrary, when equal width was USD 136.0, it was improper since we have 10 sections with the too much valid data of 34 as shown in Table 4. Note that this was very

Table 3
Classification of maintenance data by major parts

Time (month/year)	Detailed repair data	Cost (USD)	Major parts
12/2011	Dewatering facility cake conveyor reducer repair	$818	Conveyor
12/2013	Dewatering facility cake conveyor reducer repair	$818	Conveyor
09/2011	Sewage sludge cake roller box repair	$636	Roller box
11/2014	Sewage sludge cake roller box repair	$600	Roller box
09/2011	Sewage sludge cake roller box repair	$455	Roller box
04 / 2013	Sewage sludge cake roller box repair	$455	Roller box
06/2013	Sewage sludge cake roller box cover repair	$136	Roller box
03/2014	Cake roller box handle and ring repair	$100	Roller box
12/2011	Dewatering facility cake conveyor roller replacement	$1,118	Roller
11/2013	Dewatering facility cake conveyor roller replacement	$1,118	Roller
08/2014	Dewatering facility cake conveyor roller replacement	$1,118	Roller
01/2014	Cake box roller repair	$327	Box roller
01/2012	Cake box roller repair	$327	Box roller
08/2013	Polymer feed pump V-BELT replacement	$45	Polymer feed
11/2013	Polymer feed pump V-BELT replacement	$45	Polymer feed
02/2012	Polymer feed pump inverter fan replacement	$18	Polymer feed
01/2014	inverter adjustable resistance replacement	$24	Polymer feed
06/2013	Polymer feed pump inverter repair	$23	Polymer feed
07/2012	Sludge supply pump universal joint replacement	$636	Sludge feed
04/2013	Sludge supply pump universal joint replacement	$636	Sludge feed
01/2014	Sludge supply pump V-BELT replacement	$41	Sludge feed
03/2013	Sludge supply pump V-BELT replacement	$45	Sludge feed

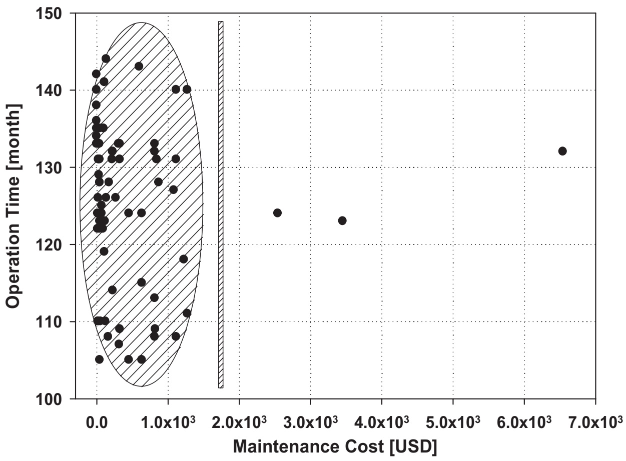

Fig. 4. Historical data distribution pattern and their analysis.

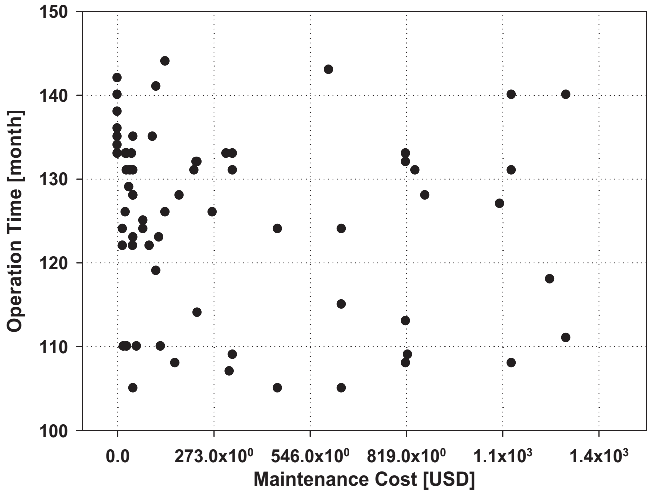

Fig. 5. Historical data distribution with maintenance cost less than 1,400 USD with equal width of 273 USD.

complicated situation for data analysis. When comparing equal width of USD 182.0 and USD 273.0, the valid data were 29 and 28, respectively. Therefore, we chose the valid data of USD 273.0. Finally, we obtained average occurrence period ($\bar{T}$) and average repair cost ($\bar{C}$) using historical data divided into eight section by discrete method as shown in Fig. 5. Gaussian distribution with ($\pm 2\sigma$) was used to reduce data interruption. The results are summarized in Table 5.

3.2. The prediction of CMC and CDF for each section

Fig. 6 is a graph for cumulated maintenance cost (CMC) and CDF prediction obtained from repair and replacement cost in section 2 of Fig. 5. CDF, displayed in dotted line in the figure, is obtained with monthly accumulated probability of failure and renewed if it reaches the limit of 0.6321. If the CDF reaches the limit, an action of repair will mathematically happen. The cost spent for this repair is called CMC. Section 6, which is equivalent to maintenance cost from $2,455 to $2,728, shows a return period of 124 months. Therefore, the maintenance will happen within 385 months as shown in Fig. 7. Section 8, which is equivalent to maintenance cost over $6,545, shows a return period of 132 months. Therefore, the maintenance will happen within 290 months as shown in Fig. 8.

3.3. Obtaining LCC of dewatering facility

Fig. 9 is LCC results of dewatering facility obtained from maintenance cost data and Bernoulli trials. It was expected that the maintenance cost reaches $234,778 after 385 months from its installation. The LCC exceeded the $180,000 which is initial installation cost of dewatering facility. Since the maintenance cost was bigger than installation cost, the facility owner would consider replacing aged equipment at some point of operation. The LCC analysis could be used for decision making.

3.4. Obtaining VaR

We calculated average occurrence probability and repair cost in Table 5, which is plotted as Fig. 10. We also added VaR

Table 4
Standard deviation of equal width division

	Equal width (unit: USD)			
	136.0	182.0	273.0	364.0
	Standard deviation (σ)			
Section 1	365,100	482,409	669,636	1,026,527
Section 2	436,791	464,909	499,082	824,327
Section 3	72,727	–	157,464	3,051,373
Section 4	–	157,464	917,591	713,245
Section 5	157,464	194,964	713,245	–
Section 6	194,964	472,382	–	–
Section 7	–	–	–	–
Section 8	–	–	–	
Section 9	–	–		
Section 10	–	–		
Number of valid data within ±2σ	34	29	28	18
Number of sections	10	10	8	7

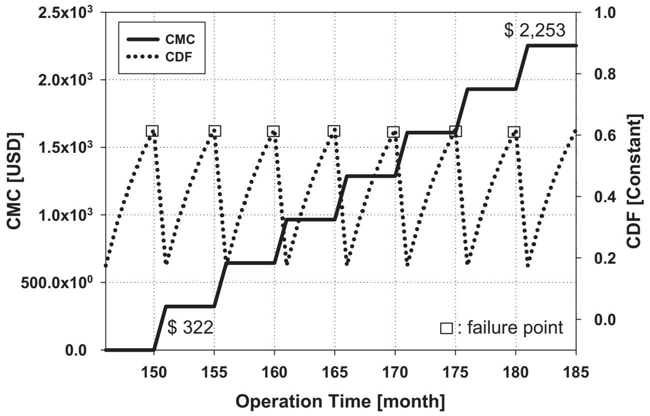

Fig. 6. CMC result for section 2 with return period of 5.71 months.

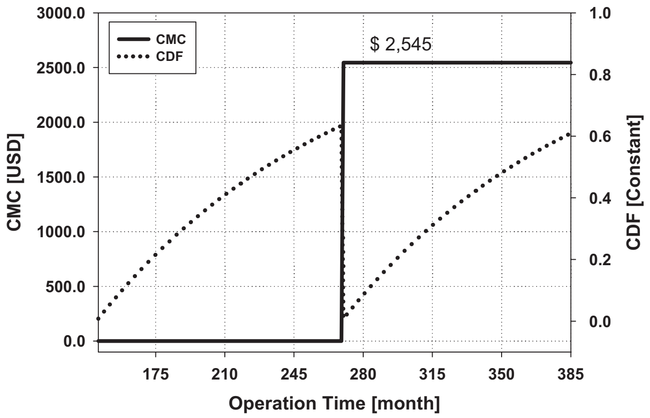

Fig. 7. CMC result for section 6 with return period of 124.0 months.

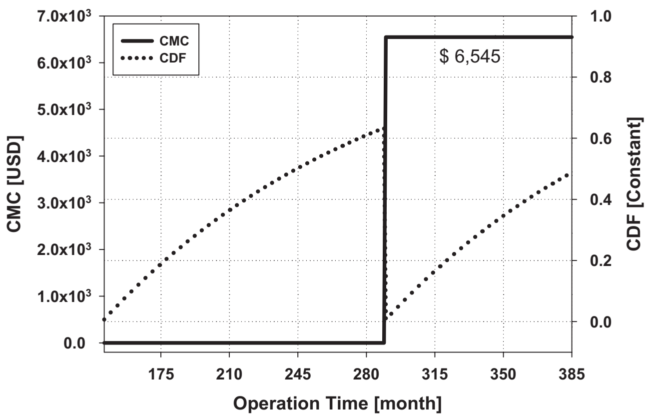

Fig. 8. CMC result for section 8 with return period of 132.0 months.

Table 5
The statistical result of Gaussian distribution analysis

	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7	Section 8
Average occurrence period ($\bar{T}$) (month)	1.11	5.71	10.00	5.00	6.67	124.00	123.00	132.00
Average occurrence probability ($\bar{P}$)	0.9000	0.1750	0.1000	0.2000	0.1500	0.0081	0.0081	0.0076
Average repair cost ($\bar{C}$) (USD)	$93	$325	$636	$831	$1,227	$2,545	$3,455	$6,545

results in the figure. The x axis is the average cost ($\bar{C}$) and y axis is the average probability ($1/\bar{T}$). The value of k in Eq. (6) is 1.29, assuming that the confidence level is 90%. The maximum VaR of the dewatering facility was calculated to be \$4,590. The possibility to exceed this cost was within 10% [13]. Note that the method used in this study to calculate VaR assumes that cost probability is normal Gaussian distribution and that the incident of future will be repeat in the same pattern like past.

3.5. Maintenance cost comparison for reactive and proactive management

Proactive management is a maintenance method to repair or replace parts by scheduled plan before they are broken. Regular maintenance plan and action are required for proactive management. Proactive management cost (PMC) is the cost occurred by proactive management [15]. On the contrary if equipment is repaired after they are broken, it is defined as follow-up management. The cost for follow-up management is defined as follow-up management cost (FMC) [15]. Fig. 11 shows PMC results, which is sum of individual CMC from eight sections. The total cost of PMC was estimated to be USD 163,250 from the beginning of operation to 385 months.

FMC was calculated to be USD 4,590 at section 3.4 using VaR. For follow-up maintenance, we need to consider additional cost from fatigue of equipment. Repair after broken down makes it difficult to recover completely at initial state since it affects the durability of equipment, which will decrease its life span. This is defined as deterioration cost [14]. Fig. 12 shows FMC results, which is sum of individual CMC from eight sections. The total cost of FMC was estimated to be USD 200,930 from the beginning of operation to 385 months.

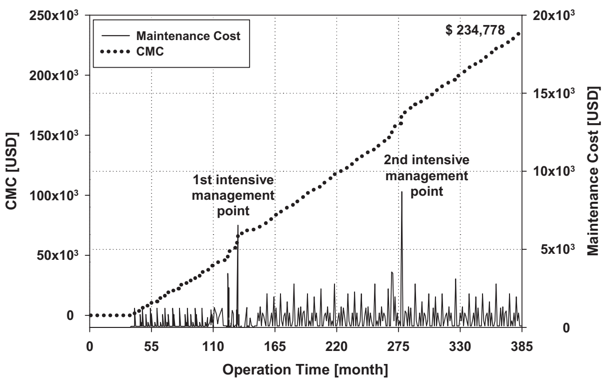

Fig. 9. Estimated life cycle cost the facilities over total operation time.

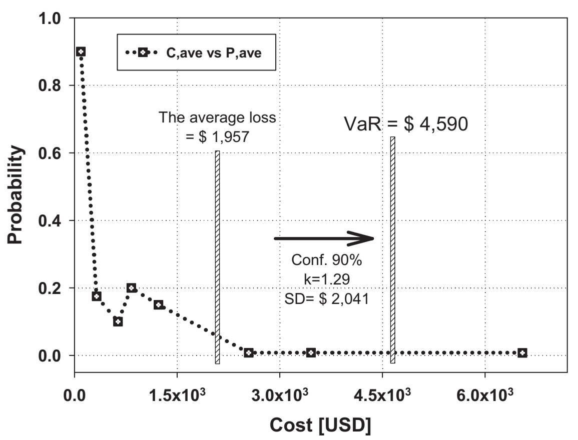

Fig. 10. Probability vs. cost (k = 1.29) for value at risk.

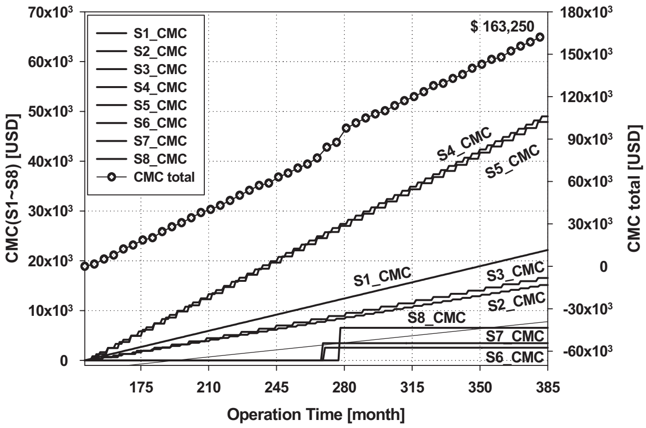

Fig. 11. Cumulative CMC for the sections 1–8 (146–385 months) in the proactive point of view.

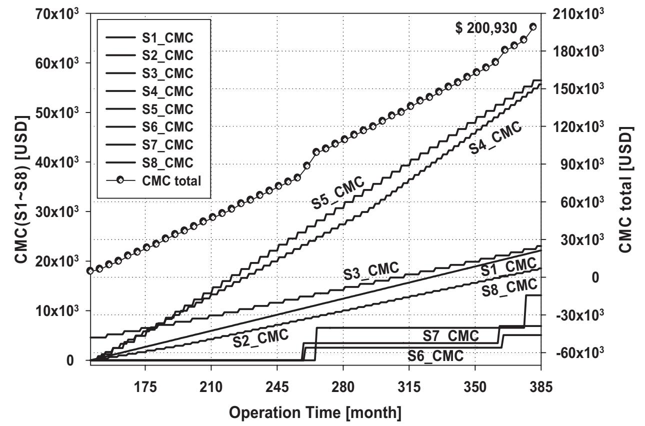

Fig. 12. Cumulative CMC for the section 1–8 (146–385 months) in the follow-up point of view.

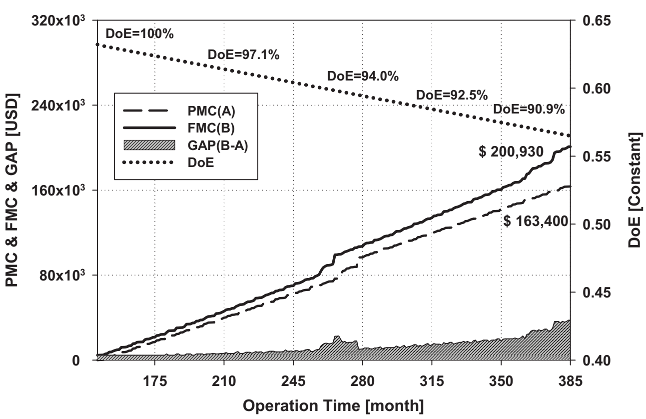

Fig. 13. PMC, FMC, and DoE over operation time.

Fig. 13 is a comparison graph for PMC and FMC results. The decrease of durability (DoE) of equipment by FMC is also shown in the graph. The decrease rate was assumed to be 0.0443% a month, which is equivalent to 0.5316% a year [16]. The solid part in the lower part of the figure is the gap between PMC and FMC. The maximum difference at 285 months between PMC and FMC was USD 37,530. FMC was higher than PMC in the figure.

Hence, proactive maintenance is beneficial to facility owners over reactive maintenance in this respect. It was also shown that the gap was highest between 245 and 280 months.

4. Conclusions

We developed a method to forecast future maintenance cost of a dewatering facility in a wastewater treatment plant. We also developed a method to obtain average occurrence probability and average occurrence cost using the data grouping method with equal width of the valid data of USD 273.0. And then, we predicted CMC and CDF. CDF is obtained with monthly accumulated probability of failure and renewed if it reaches the limit of 0.6321. LCC results of dewatering facility were obtained from maintenance cost data and Bernoulli trials. It was expected that the maintenance cost reaches $234,778 after 385 months from its installation. We calculated VaR using average occurrence probability and repair cost. The maximum VaR of the dewatering facility was calculated to be $4,590. We calculated PMC and FMC using VaR and LCC. The maximum difference at 285 months between PMC and FMC was USD 37,530. FMC was higher than PMC in the figure. Hence, proactive maintenance was beneficial to facility owners.

Acknowledgments

This work was supported by POSCO E&C and BLUE O&M as "Development of Operation and maintenance management solutions utilizing the method of asset management in sewage treatment plant (R-2015-00362)."

References

[1] C.Y. Song, Analysis of maintenance costs through the maintenance cycle and maintenance cost ratio for educational building, Korean Inst. Educ. Facil., 54 (2013) 153–161.
[2] OWASA, Using Asset Management to Develop and Gain Support for Your Capital Improvement Program, Orange Water and Sewer Authority, Carrboro-Chapel Hill Community in North Carolina, 2015.
[3] J.E. Bae, Comparison of Effectivity of Sewage Plants According to Their Managing Type, Keimyung University, 2005.
[4] M.Y. Cho, M.J. Chae, J.R. Kim, G. Lee, J.W. Park, Development of Water and Wastewater Pipeline Total Asset Management System, 2nd Ed., Korea Institute of Civil Engineering and Building Technology, 2009, pp. 137–157.
[5] M.H. Lee, A study on the durable year-oriented LCC calculation of resource recovery facilities, Chung-Ang University, 2009.
[6] H.G. Kang, A study on Life Cycle Cost Analysis of Reinforced Concrete structures using the Asset Management Concepts, Sunchon National University, 2008.
[7] Korea Environment Corporation, Statistical Analysis and Structural Design Analysis Report for Waterworks Facility Asset Management, 2015.
[8] Thora Burkhardt, David Kerr, City of Annapolis Department of Public Works Asset Management Program, Water Infrastructure, AWWA, 2015, pp. 17–30.
[9] H.N. Cho, C.G. Lim, Y.M. Choi, G.H. Park, Life-Cycle Cost Analysis for Infrastructure Systems, Goomibook, Seoul, Korea, 2008.
[10] P.N. Tan, M. Steinbach, V. Kumar, Introduction to Data Mining, 1st Ed., Addison Wesley, 2006, pp. 19–59.
[11] IHI, Belt Press Dehydrator Product Information (About Components and How It Works), 2016, Available at: https://www.ihi.co.jp/separator/kr/products/other/belt_press.html.
[12] H-S.A. Alfredo, H.T. Wilson, Probability Concepts in Engineering, 2nd Ed., Wiley, 2007, pp. 105–118.
[13] G.O. Lyu, Corporate Risk Management, Moonyoungsa, Seoul, Korea, 2012, pp. 158–159.
[14] D.H. Han, G.H. Min, A Practical Introduction to Project Risk Management, Ireatech, Korea, 2012, pp. 20–27.
[15] S.H. Park, The Maintenance Strategy of the Existing Bridge Based on Optimal Preventive/Corrective Maintenance, Seoul National University of Science and Technology, 2009.
[16] C.S. Lee, Development of Asset Management Method for Operational Cost Optimization of Water Treatment Plant Using UF Membrane, Dankook University, 2016.