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Economical selection of optimum pressurized hollow fiber membrane modules in water purification system using RbLCC

Chul-sung Lee[a], Young-wook Nam[b] and Doo-il Kim*

Department of Civil and Environmental Engineering, Dankook University, 251 Jukeonro Sujigu Yonginsi Gyunggido, 16890, South Korea

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Abstract. A water treatment utility in South Korea operates a large system of pressurized hollow fiber membrane (PHFM) modules. The optimal selection of membrane module for the full scale plant was critical issue and carried out using Risk-based Life Cycle Cost (RbLCC) analysis based on the historical data of operation and maintenance. The RbLCC analysis was used in the process of decision-making for replacing aged modules. The initial purchasing cost and the value at risk during operation were considered together. The failure of modules occurs stochastically depending on the physical deterioration with usage over time. The life span of module was used as a factor for the failure of Poisson's probability model, which was used to obtain the probability of failure during the operation. The RbLCC was calculated by combining the initial cost and the value at risk without its warranty term. Additionally, the properties of membrane were considered to select the optimum product. Results showed that the module's life span in the system was ten years (120 month) with safety factor. The optimum product was selected from six candidates membrane for a full scale water treatment facility. This method could be used to make the optimum and rational decision for the operation of membrane water purification facility.

Keywords: asset management; pressurized hollow fiber membrane; risk-based life cycle cost (RbLCC); pin-repairing data; poisson's probability model

1. Introduction

Infrastructure's asset management of water treatment utilities has become important because governments' budget pressures tend to increase rapidly in maintenance costs due to aging of infrastructure (Alegre *et al*. 2007), which requires effective management of the aged utilities to reduce their replacement cost for recovering their ability (Park *et al*. 2016). The asset management is a way to maintain the value of infrastructures on the base of the triple-bottom-line thinking that integrates social, environment, and economic responsibilities (Gimenez *et al*. 2012). Since water treatment utilities do not have enough budget for renewal of their facilities, these utilities need to prepare effective strategy to replace their aged components and to minimize their maintenance

*Corresponding author, Associate Professor, E-mail: dikim21@dankook.ac.kr
[a]M.Sc, E-mail: hiznow@hanmail.net
[b]M.Sc, E-mail: youngwnam@naver.com

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costs through analysis of quantitative value at risk and life cycle cost using the asset management for sustainable management (Strazza *et al*. 2015).

In the recent study for a water treatment plant in South Korea using pressurized hollow fiber membrane (PHFM) modules, it was required to replace aged modules within roughly two years (Lee 2016), which resulted from analysis of the data of operation and maintenance. For this requirement to exchange whole active modules in the plant, it was necessary to decide a reasonable time for a plant. It was also questionable whether repurchasing the active modules is a better economical remedy or buying different types of the modules are more reasonable in an economical aspect. The newly chosen modules will be used for more than 5 years and be difficult to be exchanged if a certain type of PHFM modules is selected as the counterplan in the operation of the system. Thus, the administrators need to consider to evaluate both its initial purchasing cost and its value at risk, which is stochastically happened on the failure modules dependent on its physical deterioration as time elapsed.

Conventional studies on membrane selections have focused on treatment level depending on the original purposes, including how much degree water is purified to use for specific industry fields, or to use in daily activities of residential water consumers (Rojas-Serrano *et al*. 2015). Additionally, managers of water purification plant technically need to consider relationships between membrane's chemical characteristics and cleaning chemicals that are frequently used in cleaning and inspection process to select a optimal membrane type because some membranes have weak characteristics on their cleaning chemicals such as NaOH, H_2SO_4 and HCl which are used to remove contaminants on their surface. Membranes' physical properties such as its tensile strength and flexibility are needed to take into consideration depending on its physical pressure environment to select a membrane type. Some studies have shown that it is more important to use proper pretreatment depending on the feed water characteristics rather than membrane in order to increase the operating efficacy in facilities (Mallevialle *et al*. 1996).

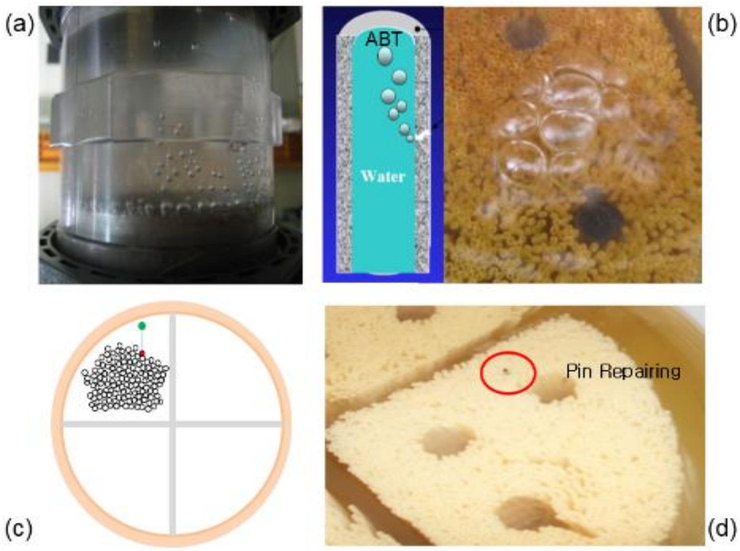

Fig. 1 Images showing the pin repairing events: (a) detection of air bubble using PDT, (b) checking damaged positions through the air bubble test, (c) action of pin repairing on hollow fiber membrane, (d) the result of pin repairing (Lee 2016)

According to economical perspective, the RbLCC, considering together both the initial purchasing cost and the value at risk, could be a critical tool in the process of decision-making (Jo *et al*. 2009). Since comparing RbLCC values of each products in a water treatment plant, operators can take an advantage of doing the proper rational decision to select an optimal product economically from all the alternatives.

The objective of this paper is to develop a method to choose optimum membrane modules estimating the RbLCC of possible candidates to minimize the replacement cost, based on the historical field data of a water treatment plant in South Korea.

2. Materials and methods

2.1 Properties of PHFM and module

The properties of PHFM used in the water treatment plant are made from PVDF (Polyvinylidene Fluoride). Its micro pore size is 0.05 μm. Inner diameter in PHFM is 0.07 mm. Outer diameter is 1.3 mm with asymmetrical structure. Its average operating capacity per module is 112 m^3/day. Filtering velocity is 1.5 m/day. Each module is consisted of 8,900 membrane fibers. The valid surface area of its membrane is 75 m^2/module.

2.2 Evaluation of valid life in PHFM based on the pin-repairing data

The PHFM's life were evaluated using the pin-repairing data which included its operation and maintenance environment in a water treatment plant. The life span of used PHFM modules might be related to another modules' life as long as they were employed in the similar environment. The pin-repairing was conducted by closing a valve in the PHFM and exerting air pressure, in which conditions the micro bubbles were detected in the middle of the inspection process. When the proportion of inactivated PHFM after pin-repairing was above 0.45% in the module, these modules were considered to be failure by an operators. A broken module was replaced with a new module. The criteria was established because the module had a spatial limit to accept many pins on hollow fiber membranes. Note that the module's capability decreases and pin-repairing becomes more difficult as the number of pin repairing in one module increases. Hence, we defined the life span of one module in the system were the time for repaired fiber to reach more than 0.45 %.

2.3 Assessment of risk-based LCC

The Poisson model was used to obtain the failure probability that were used to expect the life span of a PHFM, which is how many modules in the systems could be in failure in a particular period. The value at risk was taken by multiplying the number of accumulated failure modules with its module price (Han *et al*. 2012). The RbLCC was calculated by combining the initial cost and the value at risk without the partial risk value during its warranting period.

3. Results and discussion

3.1 Evaluation of valid life span in PHFM with its pin-repairing data

It was assumed that the number of PHFM in a module was k (8900 ea) and its own life span was τ (month) and its failure characteristic was independent each other. According to the pin-repairing data from January of 2011 to December of 2014, it was possible to formulate the maintenance rate of pin-repairing (Kim 2007).

$$h(t) = \frac{f(t)}{S(t)} \tag{1}$$

$h(t)$ as shown in Eq. (1) had a relationship with both non-failure probability function $S(t)$ and probability density function $f(t)$. This formula could be transformed by its integration as shown in Eq. (2) and Eq. (3).

$$\mathrm{H(t)} = \int_0^t \mathrm{h(t)dt} \tag{2}$$

$$S(t) = \mathrm{e}^{-\int_0^t \mathrm{h(t)dt}} \tag{3}$$

Thus, the number of non-failure PHFM during operating time, $R(t)$ was shown as Eq. (4).

$$R(t) = k \cdot S(t) = k \cdot \mathrm{e}^{-\mathrm{H(t)}} \tag{4}$$

When there was more than 40 ea of pin-repaired PHFM in a certain module, this module could be regarded as losing its effective function as well as be replaced with new module instantly in the system by operating regulation in a water treatment plant. If the ratio pin-repaired PHFMs and total ones exceed 0.45 % in a module, the module could be considered to be failure. Hence, the life span of a module (τ) was a time when the proportion ($R(t)$ / k) reached 99.55% using Eq. (5) and Eq. (6).

$$\mathrm{e}^{-\mathrm{H(t)}} \leq 0.9955 \tag{5}$$

$$t \geq \tau = H^{-1}(ln\frac{1}{0.9955}) \tag{6}$$

Based on the introduced mathematical concepts, the formula of $h(t)$ could be described by both the number of pin-repairing of each month ($\Delta G(t)$) and its accumulated number $G(t)$ in the name of the name of the 3rd System for 36 months. The formula of $h(t)$ was shown as Eq. (7).

$$h(t) = \left[\frac{\Delta \mathrm{G(t)}}{M \cdot k - \mathrm{G(t)}}\right] \cdot \frac{1}{M} \tag{7}$$

M in Eq. (7) was 42 ea which was the number of total modules composing the system. k was 8900 ea which was the number of total PHFM in a module. Fig. 2 was the increasing tendency in the number of pin-repairing affair. Fig 3 was the estimation curve of $h(t)$ in the water treatment plant during 36 months.

The $h(t) \cdot 10^9 = \mathrm{a} \cdot \mathrm{t^b}$ used in this study was assumed to be $h(0) = 0$ at initial state. Using $h(t)$, PHFM module's valid life span (τ) were expressed as Eq. (8). Parameters 'a' and 'b' could be obtained using ΣSS in order to determine its valid life span (τ) as shown Fig. 3 and Table 1. Although 'a' and 'b' parameters did not describe properties and influences of operating & management, they are used to search for pin-repairing tendency based on their history data.

$$\tau = \left[10^9 \cdot \frac{b+1}{a} \cdot ln(\frac{1}{0.9955})\right]^{b+1} \tag{8}$$

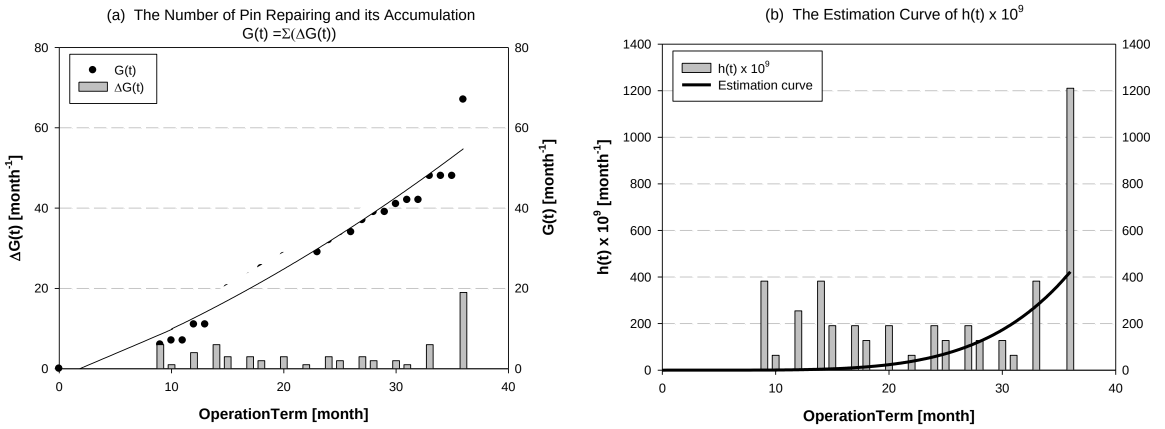

Fig. 2 (a) Number of repaired pin $\Delta G(t)$ and its accumulation $G(t)$, and (b) the estimation curve of $h(t)\times 10^9$ in the water treatment plant for 36 months

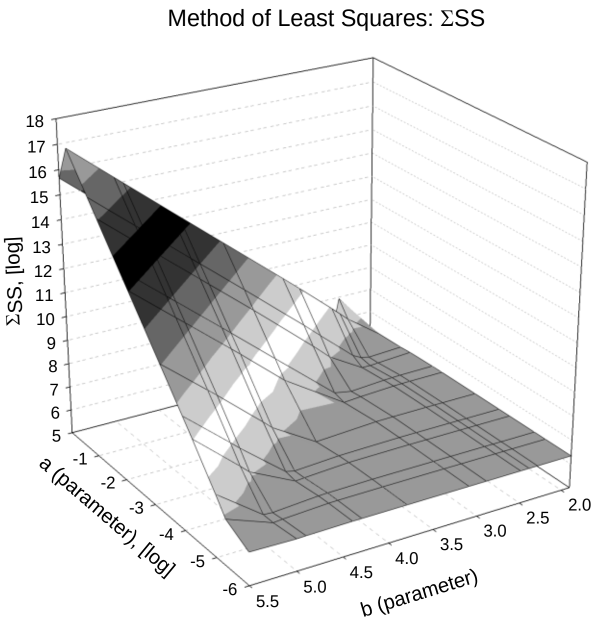

Fig. 3 Results of ΣSS of $h(t) \cdot 10^9 = a \cdot t^b$ with various '*a*' and '*b*' parameters

Table 1 was calculated to search the proper life span using minimum ΣSS value with controlling parameters '*a*' and '*b*' to describe the trend of pin-repairing in the future based on their historical data. More cases with diverse parameters '*a*' and '*b*' are shown in the Fig. 3. As being seen in both Fig. 1 and Table 1 with diverse parameters for individual cases, the minimum value was 1,473,262 when parameter '*a*' and '*b*' were 0.00001 and 4.9 respectively, from which the module's life span (τ) in the system was127.6 months. Another proper values for the module's life span (τ) were 140.2, 146, and 164.4 months, which indicated that the range of modules' life span in the system might approximately range from ten years (120 month) to fourteen years (168

Table 1 Life span (τ) and ΣSS obtained from controlling parameters 'a' and 'b'. The proper cases marked as 'Prop.'. The best case is the minimum of ΣSS in this method, marked as 'Min.'. Unsatisfying cases are marked as '*X*'

	a	b	T	ΣSS	Assessment
I	0.05	2.4	313.4	1551192	X
II	0.05	2.5	268.1	1558333	X
III	0.01	2.9	234.7	1528795	X
IV	0.005	3.1	215.6	1525028	X
V	0.0005	3.8	164.4	1505795	Prop.
VI	0.0001	4.3	140.2	1514887	Prop.
VII	0.00005	4.4	146	1506499	Prop.
VIII	0.00001	4.9	127.6	1473262	Min.
IX	0.00001	4.3	216.6	2063617	X
X	0.000005	4.3	246.8	2143228	X
XI	0.000005	5	132.5	1548322	Prop.
XII	0.000001	4.9	188.6	2090571	X
XIII	0.000001	5.5	118.0	2239159	X

month). Therefore, the module's valid life span (τ) in the system in the water treatment plant was estimated to be ten years (120 month).

3.2 Evaluation of the failure probability with poisson distribution with its valid life span (τ)

If the system consist of modules with similar characteristic and each module's life span (τ) has in the average range, the average possibility of failure become $1/\tau$. Each module has only one chance to be failure during its life span because it was instantly replaced with new product having the identical properties in order to maintain the plant.

The valid life span was used as a factor of failure in Poisson's probability model (Ang *et al*. 2007), which implied how much the failure event in the same modules of the system might happen during the operating time. The Poisson's probability model had several constraints to be used in the system with the number of modules. They were the random occurrence of failure modules and the independence of its occurrence among modules. Its occurrence probability was also calculated by multiplying its average occurring chance and time interval (Δt) together. Additionally, its average occurring chance was affected by deterioration ($D(t)$) of its life span. $D(t)$ is related to membrane's chemical and physical properties, feed and pretreatment conditions, and managing capabilities which lead to influence on its LCC analysis. $D(t)$ was assumed to be constantly reduced by 0.0443% per month on its module's life span in the analyzing period. Thus, the Poisson's Probability Mass Function (PMF, $P(x, t)$) in the time interval (Δt) was shown as Eq. (9). Here, x means its possible failure numbers in the same time.

$$P(x,t) = \left[\frac{t \cdot \left[\frac{D(t)}{\tau}\right]}{x!}\right]^{x} \cdot e^{-t \cdot \left[\frac{D(t)}{\tau}\right]}$$

$$\left(x = 1, 2, 3, \ldots, \mu\ (EA)\right) \quad (t = 0, 1, 2, 3, \ldots, t(month)) \tag{9}$$

By adding each expectation value in failure numbers per month, the failure expectation value, $E_m(t)$ was calculated as below formula Eq. (10). Using $E_m(t)$ and the total module number (μ) in its system, the failure occurrence ratio per month, $h_m(t)$ in each month can be shown as Eq. (11).

$$E_m(t) = \sum_{x=1}^{x=\mu} x \cdot P(t, x) \tag{10}$$

$$h_m(t) = \frac{E_m(t)}{\mu} \tag{11}$$

And, there were ignorance in its values less than 0.5 into 0 in $n_f(t)$, such as ($IF(n_f$<0.5,0, IF (n_f≥0.5, n_f))), in order to represent the actual maintenance data in the water treatment plant as well as to prevent its estimations from being exaggerated by minor values' interventions as below Eq. (12).

$$n_f(t) = \mu \cdot h_m(t) \tag{12}$$

Therefore, from the initial time (t=0) to predictable aiming spot (T), the possible number of failure modules in the system could be estimated using Eq. (13).

$$N_{fail}(T) = \sum_{t=0}^{t=T} n_f(t) \tag{13}$$

As being calculated by combining the initial cost and the value at risk without its repair within its warranting period, individual RbLCC is illustrated in Eq. (14). Here, C_{Ini} was the initial cost. C_m was the risk value of one failure module. W is the period of warranty.

$$RbLCC = C_{Ini} + C_m \cdot [N_{fail}(T) - N_{fail}(W)] \tag{14}$$

Table 2 Properties and information on candidate membrane modules (The system's area: 3,150 m^2)

	A	B	C	D	E	F
Model	HIFIM	HFU	HFTS	HFP	PF	UNA
Materials	PVDF	PVDF	PVDF	PVDF	PVDF	PVDF
Pore Size (μm)	0.05	0.01	0.05	0.1	0.1	0.1
Category	UF/MF	UF	UF/MF	MF	MF	MF
Pressure Style	Pressure	Pressure	Pressure	Pressure	Pressure	Pressure
Operating Style	Cross flow	Cross flow	Cross flow	Cross flow /Dead end	Cross flow /Dead end	Cross flow /Dead end
Membrane Area (m^2/module)	75	72	60	75	90	50
Guarantee (years)	4	5	5	5	6	6
Price per Module (1000 KRW)	5,500	5,800	4,800	6,000	7,700	4,200
Requiring Numbers (EA)	42	44	53	42	35	63
Initial Cost (1000 KRW)	269,500	253,750	252,000	252,000	269,500	264,600

(Approximately, 1 US dollars ≈ 1000 KRW)

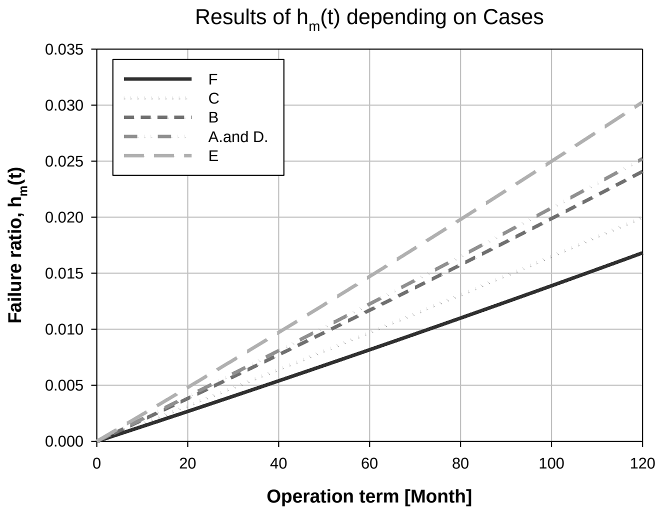

Fig. 4 Results for $h_m(t)$ for candidate membrane modules during 10 years

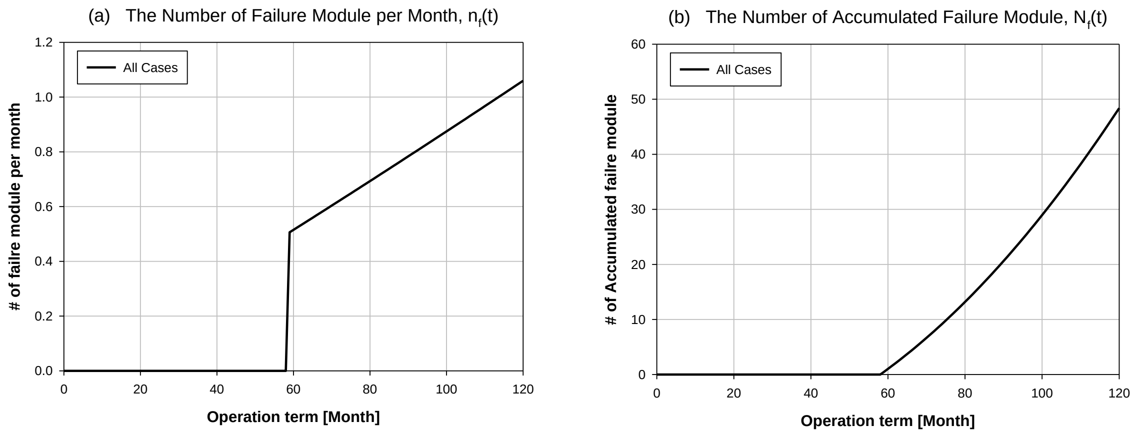

Fig. 5 (a) The number of failure module per month ($n_f(t)$), (b) The number of accumulated failure module ($N_f(t)$) with τ=120 months for ten years

Hypothetical deterioration conditions $D(t)$ was assumed to be that its condition had been constantly cumulatively deteriorated by 0.0443% per month during the module's life span (Grigg 2012). If further researches on deterioration ($D(t)$) with more diverse and abundant data of pin-repairing enough to analyze either different membrane properties with the other factors or different O&M influences from many water treatment utilities, the failure probability could reflect more sophisticated LCC including membrane properties. The individual results of $h_m(t)$ for each candidate membrane could be evaluated as shown in Fig. 4.

3.3 The assessment of RbLCC for candidates

The number of failure module per month from six modules showed identical result even though each case had individual value of $h_m(t)$ depending on their particular properties. The number of

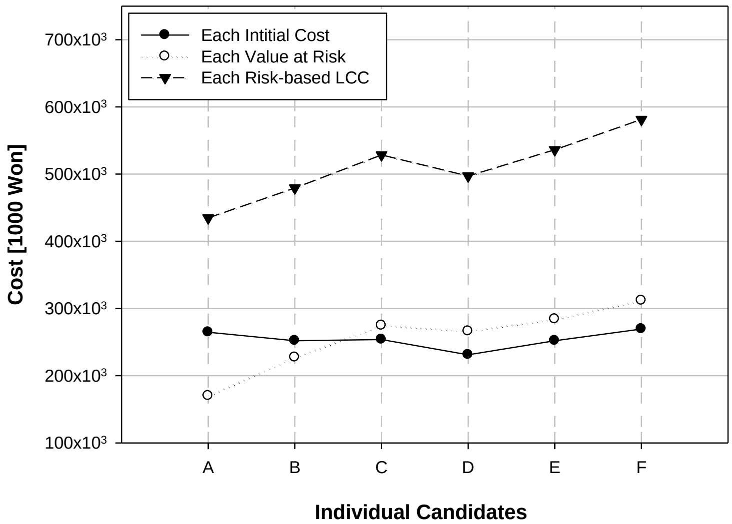

Fig. 6 The results of RbLCC for six membranes in Korean Won (KRW)

accumulated failure module per month was also equal because they shared same life span (τ) (i.e., 120 month (ten years)) from PHFM's pin repairing data under the assumption of similar operational circumstances as shown in Fig. 5.

From the above result of the number of accumulated failure with individual prices depending on its manufacturing companies, their initial cost, and the value at risk reduced by different warranty period, RbLCC values could be calculated as Fig. 6.

3.4 Selecting the optimum product by the assessment of RbLCC

As shown at Fig. 6, perspective modules with optimum value from all candidates seem to be either A or B because A is the 1st rank as 434,637,000 (KRW) and B is the 2nd rank as 479,303,000 (KRW) in RbLCC when it is not required to spend additional cost to modify the present system with 42 ea to different one with 63 or 53 ea. The optimum product would be *D* modules because *D* is the 3rd rank as 497,067,000 (KRW) of RbLCC in the analysis if additional capital cost would not be spent to modify the system components including fitting, piping, and pumps.

There is remarkable points between *D* and *E* in the Fig. 6. Even though they have the same properties except for their respective warranty period, they showed difference in their initial costs because administrators might be able to negotiate the purchasing price of module with manufacturer in order to take more discounts by reducing its guarantee period under quantitative scrutiny, for which the RbLCC in the short term might appropriately become smaller than one in the long term. For instance, if there was not an advantage of diminishing its risk value in comparisons to its extension in warranty term, this idea could not be proper in the economical aspect. On the other hand, if there was an advantage, it is worth to consider reducing its warranty term in order to diminish initial cost to set up or renew its system. Thus, the manager could take advantages of saving in the initial cost to either set up or renew its facility in the future based on this analyzing process because its data could be secured for its operation and maintenance (O&M) period.

A water treatment plant might not have their accumulated O&M data enough to apply for RbLCC in asset management and might not do their adequate efforts to develop their own original models. If these tools might be adapted to the other plant, this method might contribute for their administrators to make better decisions to reduce initial cost and renewal cost. Although we have found some difficulties to obtain O&M data and information on the other modules' life span based on the pin-repairing data in the same circumstances, more visible results of modules' life span in a plant could be expected with more data using the RbLCC model used in this study if they were used in the same environmental condition and O&M period.

4. Conclusions

Optimal membrane module was selected from six candidates through the process of finding minimum cost using RbLCC. The results showed that the tendency depended upon the amount of its warranty period and its initial cost to set up the system. This analyzing method might be valid to search proper membrane modules to consider its value at risk if its O&M circumstances were constant. It was shown that products with shorter warranty period might be more expensive in a similar operational condition with longer life span.

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