Asset Useful Life Evaluation Model by Annualized Total Cost of Ownership

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Abstract

Asset management integrates multi-functional view to achieve the effectiveness and efficiency of the assets by balancing costs, risks, opportunities, and performance benefits. However, the relation between maintenance strategy and asset Total Cost of Ownership (TCO) has not been widely discussed in previous researches. This study evaluates the useful life of a typical physical asset by considering the aspect of maintenance strategy in the TCO calculation. The maintenance and failure database are utilized to accomplish this objective. Monte Carlo simulation is used as an integrated approach in the proposed model, specifically to simulate the failure uncertainty. An equipment from a cement production plant is used as a case study to test the proposed model and results in the desired output. Therefore, the proposed model contributes to the integration of maintenance strategy and asset TCO to evaluate the useful life of an asset.

Keywords
asset management, maintenance strategy, total cost of ownership, asset useful life, and monte carlo simulation.

1. Introduction
Assets are critical for organization to ensure that the products and services give value to their stakeholders (Lima and Costa 2019). The effective management of the asset is required to achieve this objective (Lima et al. 2021). Asset management aims to realize the expected performance from all types of assets, hence helps the organization to get the most out of value from its assets (Janet et al. 2022). Depending on the objective of organization and expectation of stakeholders, value might signify different meanings (Amadi et al. 2010). Value could be tangible or intangible, financial or non-financial, and considering risks at different times in the asset's life (Lima and Costa 2019).

As a core functions of organizational strategies, asset management delivers a higher levels of customer service and reliability by allocating assets more efficiently (Konstantakos et al. 2019). Asset management integrates multi-functional view to achieve the effectiveness and efficiency of the assets, by balancing costs, risks, opportunities, and performance benefits. Understanding which decision-making level, decision situation, and life cycle stages are crictical in the asset management processes and activities (Kunttu et al. 2016). Therefore, the integration of asset life cycle is required in asset management system to manage the asset throughout its useful life.

The integration of asset life cycle in decision-making process implicates that asset management should consider a long-term objective and performance to drive the decision. Given all phases of asset life cycle are different, a multi-disciplinary approach in asset management is required (El-Akruti et al. 2013). TCO is a technique that can be implemented to accomplish this objective (El-Akruti et al. 2015). In principle, TCO takes into account all costs incurred throughout the life cycle of a physical asset including capital, operations, and maintenance cost (Duran et al. 2016).

Maintenance cost is definitely influenced by the equipment's failure rate, which further also influenced by the maintenance strategy applied. However, the consideration of maintenance strategy and its consequence are mostly still excluded in TCO discussion. Therefore, this study aims to evaluate the useful life of a typical physical asset by considering the aspect of maintenance strategy in the TCO calculation. Monte carlo simulation is used as an integrated approach in the proposed model. The results of proposed model then can be utilized further to re-evaluate the asset remaining value, further determine the most appropriate maintenance strategy and replacement time in the future.

1.1 Objectives

The objective of this study is to integrate the aspect of maintenance strategy and asset TCO to evaluate the useful life of an asset. This objective is further detailed into three fundamental objectives, including: 1) To develop a quantitative TCO model to evaluate an asset useful life. 2) To identify the effect of maintenance strategy in a wider perspective of TCO. 3) To test the proposed model using a real case study from the industrial practice.

2. Literature Review

Literature review is done by reviewing some literatures from credible sources such as handbook, journal, authorized data publisher, and other scientific publications. Three research concepts are elaborated including failure, maintenance, and TCO modeling, as this study aims to integrate the research streams of asset management and maintenance strategy. Several underlying theories are further discussed such as asset and asset management, reliability and maintainability, TCO, and Monte Carlo simulation.

In the discussion of asset, asset is defined as anythings that have substantial economic value or potential to the organization, which offers and seeks services from the organization (Baškarada and Gao 2006). Assets are classified into two categories there are tangible and intangible assets (Snitkin 2003). Intangible assets are consists of designs, knowledge, software, and intellectual property, while tangible assets are consists of liquid assets (such as cash or inventories) and fixed assets (such as building and infrastructure, IT equipment, machineries, and product or service equipment).

In relation, asset management is defined as the process of organizing, planning, and managing the acquisition, use, maintenance, repair, and disposal of asset in order to maximize the possibility to provide services and reduce associated risks and costs over the asset life cycle (Ouertani et al. 2008). In this context, TCO is a technique that can be applied to assess the entire costs of an asset within its life cycle and support the knowledge-based decision making process (Márquez et al. 2009). TCO is widely recognized as a strategic instrument that centralizes both technical and economic data (Roda et al. 2020).

Several researches have been developed in TCO, with an identical purpose to discover an accurate modeling and measuring approach. Danielis et al. (2018) considers both stochastic and non-stochastic variables in his proposed probabilistic TCO model to evaluate the purchasing of electric vehicle. Guo et al. (2022) further considered the usage pattern of electric vehicle fleet to improve his proposed TCO model. The optimization in TCO also have been developed. Huin et al. (2021) developed a TCO optimization model to determine the optimum size of powertrain component and management of energy which results in the minimum TCO of electric truck.

As a component in TCO calculation, maintenance is the combination of all technical, administrative, and managerial operations intended to retain or restore an asset into a state where it can perform the specified function (British Standards 2001). Several researches in the field of maintenance have been developed. The objective is identical to find an optimum strategy which provides a minimum maintenance cost (Velmurugan and Dhingra 2015). Chen and Zhu (2021) and Zhong and Tang (2022) developed an analytical model to find an optimum time and degree of preventive maintenance. The consideration of uncertain factors such as equipment failure and deterioration have been developed by Li et al. (2020) using a markov chain model. Further, Monte Carlo simulation also have been developed to find the reliability treshold of a specific type of repair, considering the uncertainty of both failure and maintenance consequences (Li et al. 2022).

Maintenance strategy will influence the reliability and maintenance cost of equipment. Thus, the consideration of maintenance strategy is critical to improve the quantification result of TCO. In this study, Monte Carlo simulation is used as an integrated approach to simulate the uncertainty of asset failure, which depends on preventive maintenance strategy applied during useful life. In theory, Monte Carlo simulation enables to consider various number of important aspects that analytical models find difficult to represent such as K-out-of-N, redundancies, stand-by nodes, aging, preventive maintenance, deteriorating repairs, and component repair priorities (Labeau and Zio 2002). The basic idea of Monte Carlo simulation is to generate specific random and discrete events within a computer model in order to produce a realistic lifetime scenario of the system (Rausand and Høyland 2004). By using Monte Carlo simulation, the restrictive model assumption which may cause the drifts in the cost estimation can be avoided.

3. Methods

The overall proposed model in this study is illustrated in Figure 1. There are three main set of modules including failure modeling, maintenance modeling, and TCO modeling. The objective is to integrate the aspect of maintenance strategy in TCO quantification to evaluate the useful life of an asset. In this context, the aspect of maintenance strategy will be represented by failure and maintenance modeling, while the aspect of asset management will be represented by TCO modeling.

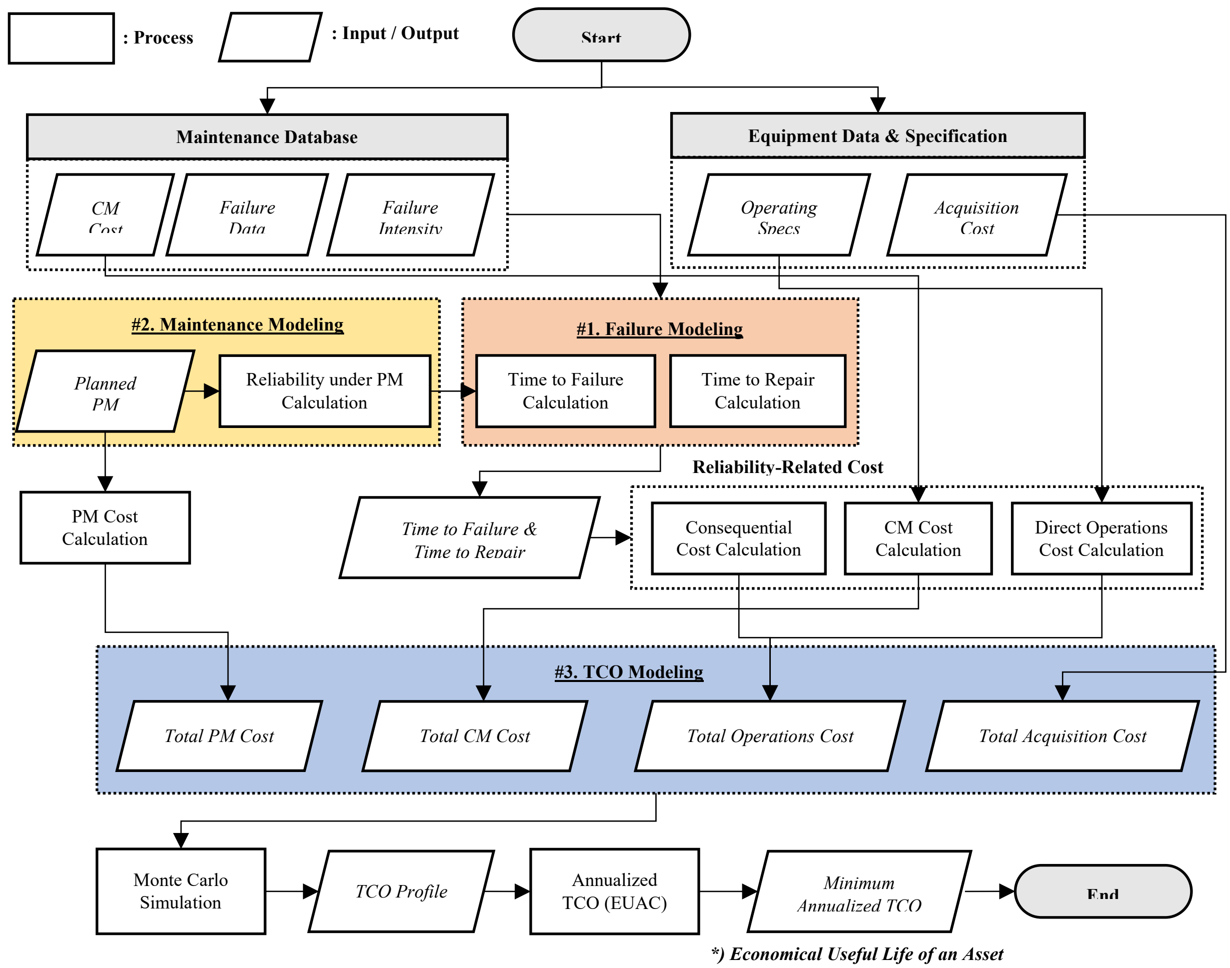


Figure 1. Proposed Asset Useful Life Evaluation Model

3.1 Failure Modeling

The objective of failure modeling is to determine the distribution parameter for uncertain inputs such as Time to Failure (TTF), Time to Repair (TTR), and failure types. TTF denotes the time interval for each failure to occur, whereas the time needed to repair the equipment relative to the types of failure is represented by TTR. By utilizing the failure and maintenance data, the identification of the initial equipment failure rate can be done by using the principle of the reliability function. In this context, Weibull distribution is preferred as it can represents a normal, exponential, and other probability distribution functions by changing the value of its shape and scale parameters. Further, most mechanical component also fit to Weibull distribution very well (Hribar and Duka 2010).

The probability density function and cumulative distribution of Weibull distribution are given by Eq. 1 and Eq.2, where β is the shape parameter and α is the scale parameter. The reliability function of Weibull distribution is given by Eq. 3 (Elsayed 2012).

$F(t) = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]$ **Equation 1.**

$f(t) = \frac{(\beta)}{(\alpha)}.\left(\frac{t}{\alpha}\right)^{\beta-1} \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]$ **Equation 2.**

$R(t) = \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]$ **Equation 3.**

3.2 Maintenance Modeling

Preventive maintenance is typically performed at a predefined intervals to reduce the probability of equipment failure. Thus, the identification of equipment failure rate within the preventive maintenance is required to determine the new distribution parameter, specifically the shape and scale parameter of TTF. The calculation is done by following the Weibul distribution and assumes that the equipment is renewed to its original condition as given in the Eq. 4, and further derived by Eq. 5 (Ebeling 2009) and Eq. 6 (Raghavan and Chowdhury 2012).

$R_m(t) = R(T)^n R(t - nT)$ for $nT \leq t \leq (n+1)T$ **Equation 4.**

$R_m(t) = \exp\left[-n\left(\frac{T}{\alpha}\right)^{\beta}\right]\exp\left[-\left(\frac{t-nT}{\alpha}\right)^{\beta}\right]$ **Equation 5.**

$f'(t) = f(t - \eta kTM).R^k(T)$ **Equation 6.**

Where $R_m(t)$ is the equipment reliability under preventive maintenance, $R(t)^n$ is the probability of surviving n maintenance intervals and $R(t\text{-}nT)$ is the probability of surviving $t\text{-}nT$ time units over the last preventive maintenance. $f'(t)$ denotes the probability density function within preventive maintenance at time t, whereas $f(t)$ denotes the probability density function without preventive maintenance. T is fixed time interval between preventive maintenance which also implied the annual frequency of preventive maintenance. k denotes the total number of preventive maintenance performed and η denotes the maintenance effect factor (assumed to be one). The new estimation of shape and scale parameter are then obtained using linearized regression principle as given by Eq. 7 (Márquez et al. 2009).

$\ln\left[ln\left(\frac{1}{1-F(t)}\right)\right] = \beta.x - \beta.\ln\alpha$ **Equation 7.**

3.3 Total Cost of Ownership

TCO is applied to estimate the value of an asset by quantifying all costs that arise within its life cycle or ownership. These costs are mainly divided into two categories, there are Capital Expenditure (Capex) and Operational Expenditure (Opex) as given by Eq. 8 (Nikolaou et al. 2022).

$TCO = \sum C_{capex} + \sum C_{opex}$ **Equation 8.**

Capex are incurred when an asset is acquired and can be quantified as acquisition cost. The characteristics are commonly obvious as it is incurred in a very early phases. Several cost components in acquisition phase may include design, development, acquisition, installation, staff training, manuals, documentation, tools and facility for future maintenance, logistics support, and so on.

In addition, Opex are incurred to keep the equipment operates in a desired state. In this study, three cost components are considered in Opex calculation including maintenance cost, direct operations cost, and consequential cost. Maintenance cost is obtained by the total of preventive maintenance and corrective maintenance cost. This study assumes that preventive maintenance are performed in a constant time interval, within a constant cost of material ($C_{material}$) and labor (C_{labor}) which escalated by inflation rate as given by Eq. 9. Thus, preventive maintenance cost will depends on the frequency of preventive maintenance performed in a year (PM_{freq}). Whereas, corrective maintenance cost will follows the equipment failure rate within preventive maintenance by using Eq. 10, where C_r denotes the repair cost incurred for each time a typical of failure happened (Raghavan and Chowdhury 2012).

$C_{PM} = (C_{labor} + C_{material})\ x\ PM_{freq}$ **Equation 9.**

$C_{CM} = \frac{(\beta)}{(\alpha)}.\left(\frac{t}{\alpha}\right)^{\beta-1} \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]\ x\ C_r$ **Equation 10.**

As for direct operations cost, it is obtained based on the cost incurred to keep the equipment operates when there is no failure happened. Its cost component may include fuel and operator cost per unit of time, which denoted as (C_f). Direct operations cost will follows the equipment availability rate over time as given by Eq. 11 (Jardine and Tsang 2021). On the other hand, consequential cost is obtained based on the cost incurred when an equipment is unable to operate due to failure. Its cost component may include opportunity cost which denoted as (*Closs*) and will follows the equipment failure rate as given by Eq. 12, which identical to the calculation of corrective maintenance cost.

$$C_{ops} = \frac{tR(t) + \int_0^t tf(t)\,dt}{t + T_r\,[1 - R(t)]}\; x\; C_f \qquad \textbf{Equation 11.}$$

$$C_{cons} = \frac{(\beta)}{(\alpha)} \cdot \left(\frac{t}{\alpha}\right)^{\beta - 1} \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] x\; C_{loss} \qquad \textbf{Equation 12.}$$

The sum of all acquisition cost, maintenance cost, direct operations cost, and consequential cost represents the TCO profile of an equipment within a *n*-periods of use. The obtained TCO value is then annualized by using the principle of Equivalent Uniform Annualized Cost (EUAC) as given by Eq. 13, where *P* denotes the present value of TCO and *i* denotes the discounted factor applied (Keown et al. 2017). Thus, an annualized TCO profile will be obtained and it will changes following the escalation of operations and maintenance cost and the diminishment of acquisition cost over time. The ideal economical useful life is when the equipment is used until it reach a minimum value of annualized TCO profile.

$$A = P\left[\frac{i(1+i)}{(1+i)^n - 1}\right] \qquad \textbf{Equation 13.}$$

3.4 Case Study Implementation

The proposed model is tested by using a real data from a cement production plant. Several data is collected including equipment specification, procurement document, and historical O&M. Equipment specification is required to identify the designed life time and operating condition of equipment, while procurement document is required to identify the detail of acquisition and other up-front costs. In addition, historical O&M data is required to identify the failure from the start of operations phase until present.

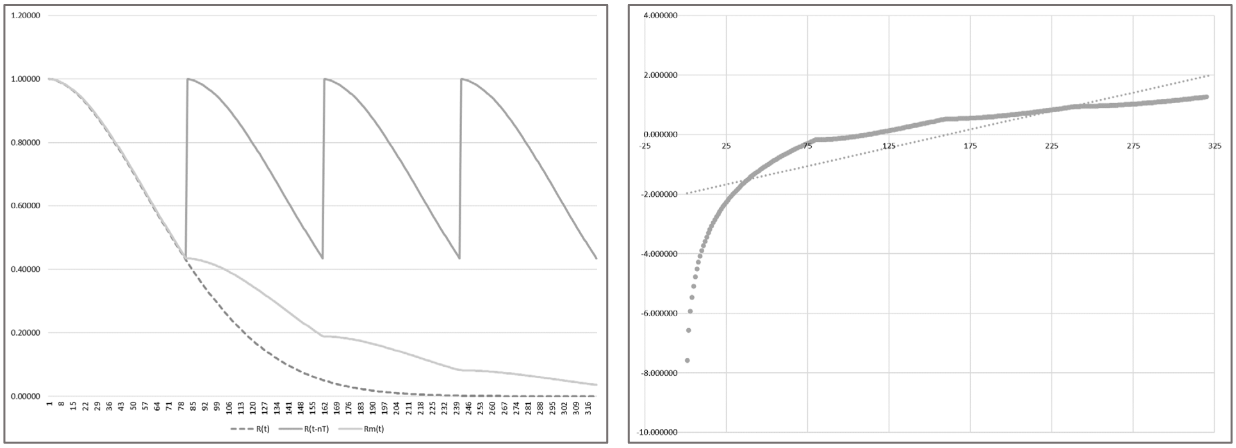
The model is tested under the basic assumption as given in Table 1, including equipment contribution, tax rate, interest rate, and escalation rate. The assumption of equipment contribution is required as this study assumes that the observed equipment is a single (stand-alone) equipment in the production system, which not interconnected to other equipment. Therefore, equipment contribution will represents a percentage value of penalty cost incurred when the production system is unable to deliver its designed capacity. The value of penalty cost is obtained based on the market valuation of product. The other assumptions such as tax rate, interest rate, and escalation rate are considered as a macro-economics parameter assumption.

Table 1. Basic Assumption Applied in the Model

No	Basic Assumption	Defined Value	Unit of Measurement
1	Equipment contribution	1.50 %	%
2	Tax rate	25.00 %	p.a.
3	Interest rate	6.00 %	p.a.
4	Escalation rate	4.50 %	p.a.

The first step is to identify the initial equipment failure rate. It is obtained by using Eqs. (1) to (3) that the value of scale parameter is 88.42 and shape paramter is 1.83 based on historical O&M data. The obtained shape and scale parameter indicates that the equipment has a tendency of increasing failure with a shape parameter value that is greater than zero in initial condition.

The next step is to identify the preventive maintenance effect on equipment failure rate, which can be obtained by identifying the shifts in the shape and scale parameter. In this case study, the strategy for preventive maitnenance is performed at 4 times a year. Thus, by using Eqs. (4) to (7), it is obtained that the shape and scale parameter are shifted into 1.43 and 119.37 respectively in the next period as shown by Figure 2. Figure 2(a) shows the reliability of equipment under the preventive maintenance, while Figure 2(b) shows the probability plot of shape and scale parameter shift. This results indicates that the preventive maintenance cause the failure to be happened infrequently.



(a) Reliability Under Preventive Maintenance (b) Probability Plot of Parameter Shift

Figure 2. Maintenance Modeling (4 Times p.a. of Preventive Maintenance)

The obtained equipment failure rate parameter are used in Monte Carlo simulation to generate the estimation of equipment TTF in the future *n*-years of operations. The simulation is done at 10,000 iterations. Figure 3. shows the example of one simulation iteration according to the amount of failure and corrective maintenance cost. The results of simulation are then used to quantify all costs that related to the reliability aspect, including total corrective maintenance cost, direct operations cost, and consequential cost.

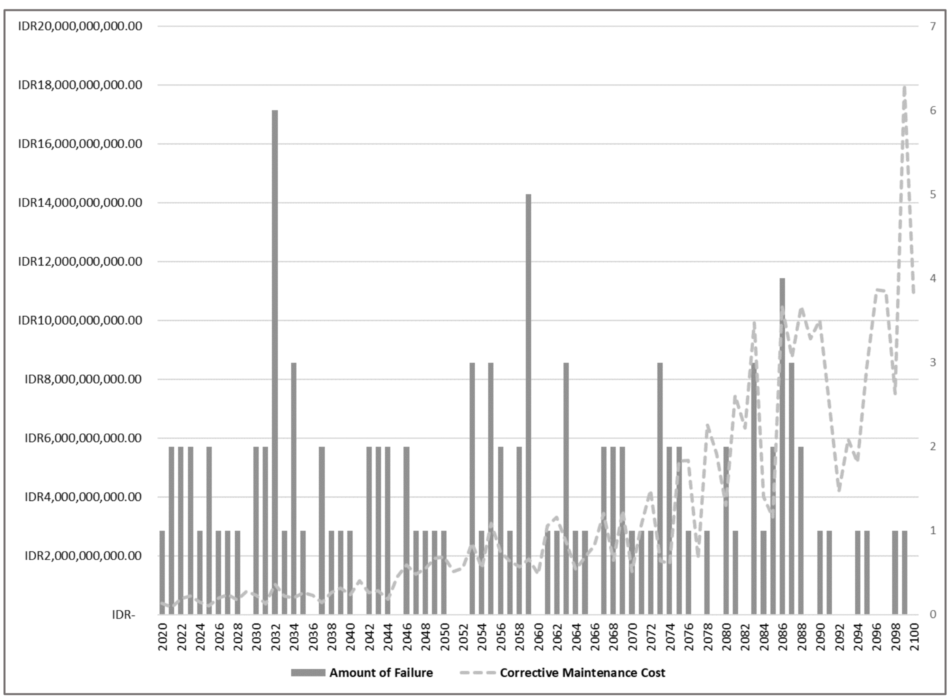


Figure 3. Simulated Failure and Corrective Maintenance Cost (one simulation iteration)

4. Result and Discussion

The combination of reliability-related cost, preventive maintenance cost, and acquisition cost result in the declining value of EUAC over time as shown in Figure 4. This EUAC value will continue to decline until it reaches its minimum value and start to escalate again. This minimum value of EUAC is interpreted as an ideal useful life as it provides a most minimum value of annualized TCO profile.

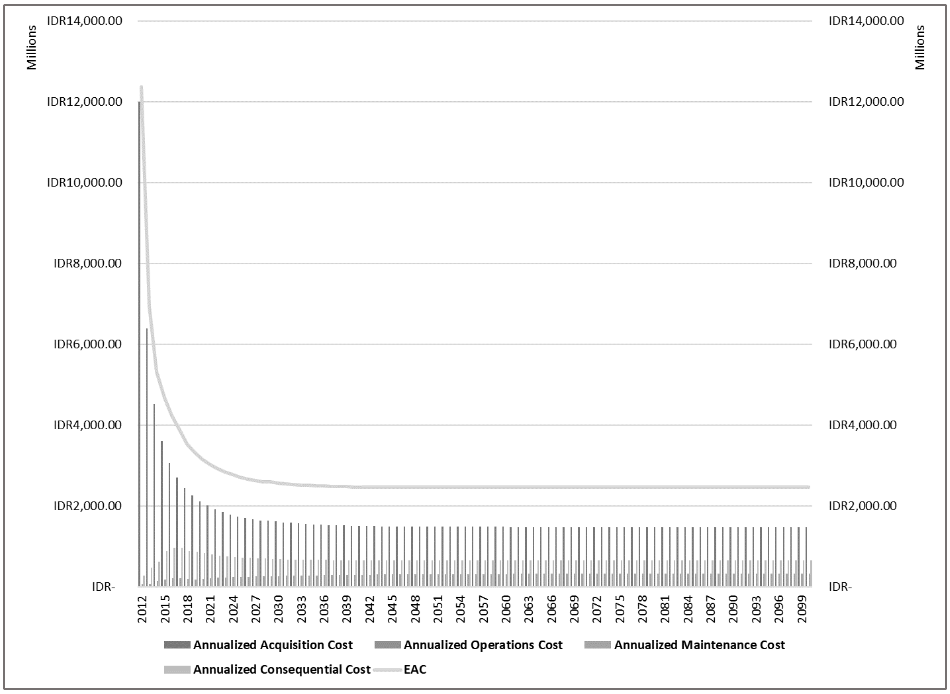


Figure 4. EUAC (Annualized TCO) Profile Over Time

The result from case study shows the minimum value of EUAC that converges at USD 169,379.31. This minimum value of EUAC converges at a year of 2046 or 34 years of useful life. The percentage value of breakdown days converges at 0.703%. It is worth mentioning that this result is still obtained under existed preventive maintenance strategy (which performed 4 times per year) and assumption that the equipment is a single (stand-alone) equipment. A more detailed results of proposed model in case study are given by Table 2 below.

Table 2. Case Study Results

Year of Equipment	*2011 (installed) ~ 2012 (operations started)*			
Objective	**Min**	**Max**	**Average**	**Standard Deviation**
Estimated minimum EUAC (US$)	163,724.14	176,827.59	169,379.31	1,604.22
Estimated useful life (years)	28 yrs (2040)	52 yrs (2064)	34 yrs (2046)	4.76 yrs
Percentage of breakdown days (%)	0.37037%	1.18056%	0.70271%	0.11098%

5. Conclusion

This study developed a model to evaluate the asset useful life, by integrating the aspect of maintenance strategy in a wider perspective of TCO. Three research concepts are elaborated including failure modeling, maintenance modeling, and TCO modeling. Model is demonstrable to deliver the expected result as tested in a case study. In industrial practice, this model has several potential benefits, including (1) Evaluate the end of economical asset useful life. (2) Estimate the remaining book value of an asset under various operating conditions. (3) Useful life database development for each specific type and condition of an asset.

For further research, the assumption about the observed equipment that stands as an independent equipment can be extended. In industrial practice, a complete production system is built by the equipment that interconnected between each other. Thus, a more precise estimation of system failure can be obtained by the evaluation of system reliability.

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