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Holistic Operation & Maintenance Excellence (HOME): Integrating Financial & Engineering Analysis to Determine Optimum O&M Strategies for a Power Plant during its Lifetime

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Abstract. Today, there is an oversupply of 23.5 GW (47.7%) in the electricity system of Indonesia. PT.PLN, the state-owned electricity company, needs decision criteria to decide whether the power plant should be continue operated, rehabilitated or demolished. Base on the literature review, none of the frameworks in the world could be used to solve this problem. Therefore, this research proposed a new method or framework called HOME (Holistic Operation & Maintenance Excellence). The method has proposed and analysed in this research combines engineering analysis (efficiency and reliability) and economic analysis, which are total cost (acquisition cost, fuel cost, operation cost, and maintenance cost) and revenue. The objective is to define decision criteria to maximize the profit and minimize the cost has spent by a power plant. The final results are the decision criteria for a power plant, wheater to continue operated, rehabilitated, relocated, or demolished. A sub-critical coal power plant, 400 MW, has been selected as a case study. Two scenarios of coals (LRC and HRC) and CF (79.46% and 60.96%) have been analyzed. Coal variation is used to evaluate its impact on efficiency and reliability, while CF change would represent the external and uncontrollable factor that impacts its revenue. The results showed that the thermal efficiency when using LRC (4,220 kcal/kg) reduced from 36.99% to 35.18% compared to HRC (4,917 kcal/kg), while the plant availability decreased from 97.93% to 97.45%. Nonetheless, the annualized profit when using LRC at the CF of 79.46% was 18.31 million USD/year, and it was a preferable option compared to 7.80 million USD/year when using HRC. Furthermore, the CF has predicted a reduction to 60.96%. In this situation, the power plant was better rehabilitated or relocated when it used HRC because it needs a minimum CF of 63.83% to get a break-even point (CF_{BEP}). Conversely, the plant could continue to operate when LRC is used because CF_{BEP} was 50.82%. Based on the analysis results, HOME is a good approach to determine and aid decision-making on the strategies required to operate and maintain a power plant comprehensively through its whole life cycle.

Keywords: Cost; Efficiency; LCM; Reliability; Revenue

1. Introduction

A coal-fired power plant is one of the most common options to meet base-load demand in the electricity system due to mature technology and competitive cost (Barros et al., 2016). It is expected to project relatively 31% of the world power generation by 2040 (IAE, 2017). The disadvantages are its negative impact on the environment, "dirty" image and the

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fact that it is non-renewable (Gonzalez-Salazara et al., 2018). It triggers the rapid development of a coal-fired power plant's technology, increasing efficiency and reducing environmental impact (Fu et al., 2015). In a competitive and uncertain market, the main factors considered for the survival of a power plant are energy, economic, social, and environmental issues (Petrillo et al., 2016; Luo et al., 2020). Certain problems need to be handled appropriately. First is the way and manner to manage the efficiency and reliability of the power plant while maintaining a safe environmental impact during the operating period, under certain government regulations. Normally, a life cycle management (LCM) plan addresses all of these issues. Formal definition of life cycle management is an integration of operation, maintenance, engineering, and business activities to manage asset condition, optimize asset life, and maximize asset return on investment. The two main elements of asset management are physical and financial asset management (Figure 1). Physical asset management is used to improve and maintain the asset condition through implementing efficiency and reliability management. Financial asset management is used to maximize asset value by reducing costs and increasing revenues.

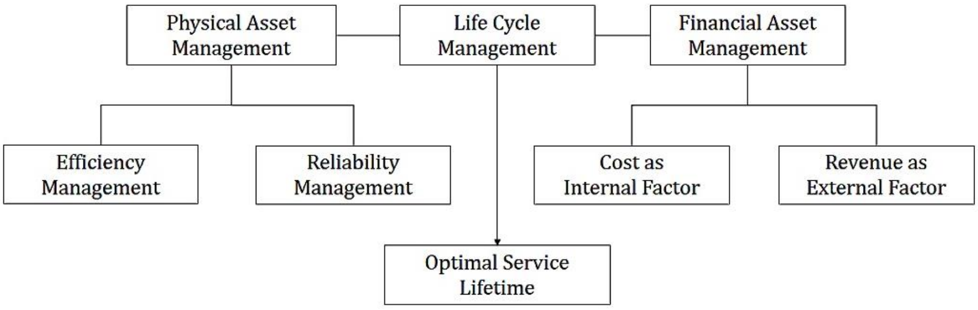
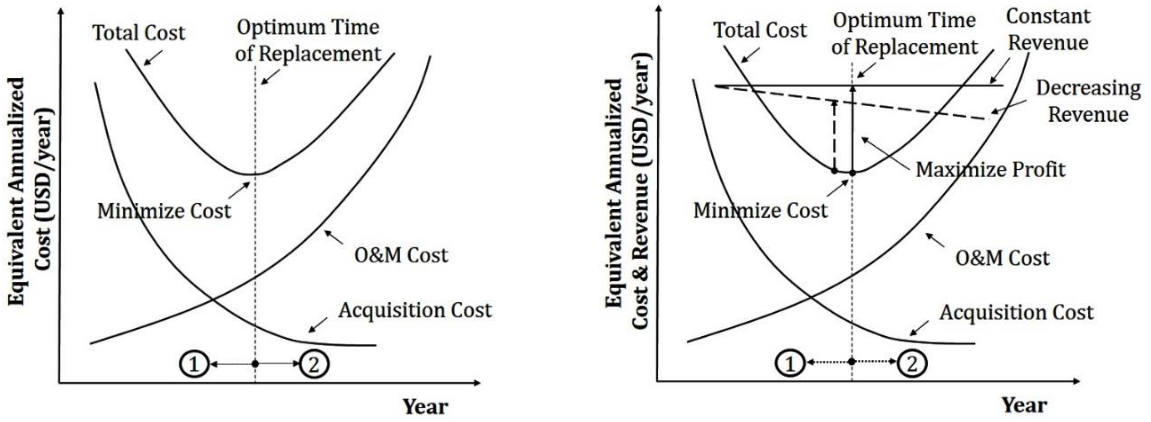


Figure 1 LCM Concept

The first LCM framework was initially developed and implemented in a nuclear power plant (EPRI, 1998). In addition, it is known as Nuclear Asset Management (NAM). The LCM framework focuses on reliability improvement (Sliter and George, 2003; Raghawan and Chowdhury, 2012). Several preliminary studies reported that reliability does not consider the power plant's efficiency (Singh and Jaswal, 2013; Pariaman et al., 2017; Melani et al., 2018). Similarly, most studies carried out in ways that increase efficiency do not take into account reliability. Furthermore, there are five factors that affect the coal-based power plant's efficiency. The first factor is design choices (Li et al., 2010; Stover et al., 2011), second is fuel strategies (Xia et al., 2014; Xu et al., 2016), third is operational practices (Xiong et al., 2012; Hübela et al., 2017), fourth is pollutant control (Munir et al., 2011), and fifth is ambient conditions (Zhang, 2015; Petrescu et al., 2017). None of the aforementioned studies analyzed both efficiency and reliability. Secondly, the power plant needs to simultaneously pay attention to sustaining its revenue. This depends on uncontrollable external factors, such as electricity demand and competitors or the market's behavior. This has become a significant challenge in the Volatility, Uncertainty, Complexity, Ambiguity (VUCA) era. The COVID-19 pandemic has significantly reduced electricity demand worldwide (Elavarasan et al., 2020). This led to a change in customers' behavior, because most people prefer to work from home. In addition, there was an increase in residential load. In contrast, the commercial and industrial ones decreased due to the slackening of business activities as an attempt to minimize the spread of the virus (Berawi et al., 2020). However, the decline in demand causes a decrease in the capacity factor (CF) of the power plant. In Indonesia, the projected CF was reported as 28.33% between 2020 and 2024 compared to 54.96% recorded in 2019, due to oversupply and COVID-19 impact (PLN, 2020). With a 47.7% (23.5 GW) reserve margin, as a consequence, several power plants have to temporarily standby or permanently shut down. This also affected the expected revenue from the initial project. Therefore, there was a need to ascertain whether the power plant was continuously operated, rehabilitated, or demolished. The objective was to either maintain the targeted financial performance or at least minimize the losses. This led to the final problems related to ways to optimize and detect the economic life of an asset. According to asset management standard (ISO 55010, 2019), the optimum time for investment intervention is the point when the overall life cycle cost of an asset is minimal (Figure 2a). In the power generation sector, this approach is established in a framework named integrated life cycle management (ILCM), as the development of LCM (Esselman et al., 2012). This focuses on the equipment or component level and ways to minimize its cost. Early replacement makes a higher total cost because the probability of failure is still relatively low compare to investment cost (zone 1). But replacement too late also makes it higher due to higher force outage cost (zone 2). Integrated life cycle management could not analyze the system or power plant level because it does not consider the revenue, while the plant has to consider both cost and revenue. The cost is dominant from internal factors and controllable by the power plant. On the contrary, revenue is more dominant from external factors and uncontrollable. Incentives on feed-in tariffs or tax credits could improve its overall cost competitiveness and make it more viable (Yang et al., 2021). In the grid system, the plant configuration has a significant impact, economically and environmentally (Destyanto et al., 2017; Xu et al., 2017; Njoku et al., 2020). Based on the references above, there is a significant gap in the studies that separately investigated efficiency, reliability, and optimum replacement analysis. None of the studies analyzed a combination of efficiency and reliability, its impact on cost and revenue, or the ways to optimize an asset life cycle at the power plant level (Wibawa et al., 2019). This led to the introduction of a novel approach called the Holistic Operation and Maintenance Excellent (HOME). This approach is based on the combination of efficiency, reliability, and replacement analysis to optimize the asset's life cycle. Furthermore, it also combines the cost and revenue of the power plant. This approach significantly analyses all the factors associated with the VUCA era. Subsequently, this research is organized as follows: first is the concepts and methodology, followed by its implementation in the power plant (industrial case study), and finally, analysis, discussions, and conclusions to determine whether or not it is suitable to address all these problems.

2. Methods

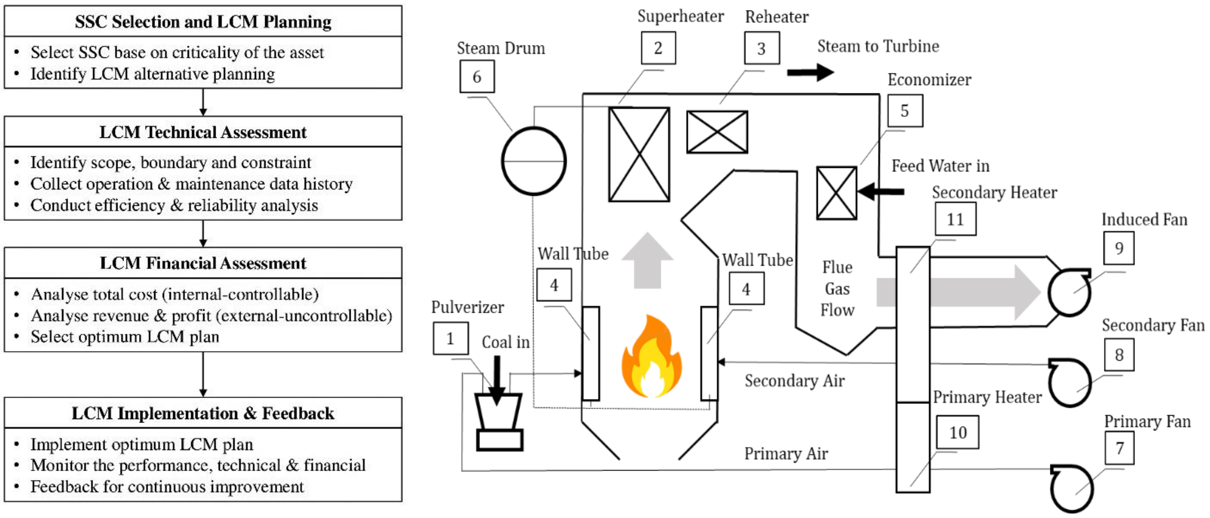
The concept of HOME focuses on the technical and financial parameters of power generation throughout its entire life, while the societal and environmental issues are assumed and maintained at an acceptable level. The objective is to determine the optimum condition using any of the LCM plans, including change of design, fuel, operation, or maintenance strategies. It also aids in determining an ideal decision (kept as it is, rehabilitated, or demolished) during the operation period and towards the end of the lifecycle. The implementation of HOME is starting from the equipment level and go through to the power plant level. The optimum condition for the power plant levels is at the point when the profit is at its maximum, rather than when the total cost is minimum, as shown in Figure 2b. The maximum profit tends to be equivalent to the minimum total cost when the revenue is constant. Generally, revenue gradually declines over time due to the involvement of a new competitor that is highly efficient and reliable. Therefore, the maximum profit tends to shift into an earlier time than it was. The power plant could continue to operate when the annualized profit increase until it reaches the maximum value (zone 1). Demolishing the power plant is an option to consider if the annualized profits start to decline after it reaches the maximum value (zone 2). This usually occurs towards the end of the power plant's lifetime. Additionally, rehabilitation or rejuvenation is an option to consider when there is feasible technology to increase profit before the decline. Conversely, the profit margin continues to decline if there is no feasible technology.



(a) (b)

Figure 2 Optimum replacement age: (a) Equipment level; and (b) Power plant level

The methodology consists of four main stages (Figure 3a). The first stage is structure, system, component (SSC) selection and identifying LCM planning. The second stage and third stage are technical assessment and financial assessments. The fourth stage is implementation and feedback review.



(a) (b)

Figure 3 (a) HOME framework and methodology; and (b) Coal power plant schematic model

3. Implementation of HOME (A Case Study)

This section explains the implementation of the HOME concept in a coal-fired power plant, 400 MW, and located in East Java, Indonesia.

3.1. SSC Selection and Identify LCM Planning

The boiler, not the turbine or generator, is the most critical SSC in the power plant which is influenced by coal variation. Figure 3b shows the model of the boiler under investigation, which consists of a furnace (pulverizer/mill, superheater, reheater, and wall tubes, economizer, and steam drum) and air and flue gas systems (primary, and secondary air fans, forced draft fans, as well as primary and secondary air heaters). There are two scenarios to study, namely coal type and CF variation. The coal variation case study was selected as an LCM alternative plan due to its impact on both efficiency and reliability. Moreover, this also directly impacts the total cost, especially that of fuel and maintenance. According to McNerney et al. (2011), the fuel cost has the highest contribution to the total cost of coal power plant (relatively 50% to 65%). The two alternatives include high-rank coal (HRC) and low-rank coal (LRC) with a low heating value (LHV) of 4.917 kcal/kg and 4.220 kcal/kg, respectively. The variation of CF represents the external and uncontrollable factors that have an impact on revenue. The two scenarios are based on the conditions before (79.46%) and after (60.96%) the COVID-19 pandemic. The data observation for each coal lasted 20 months. Therefore, fuel strategy and change in demand significantly impact efficiency, reliability, total cost, and revenue. It represents all the parameters and demonstrates the strategy the HOME framework used to solve these problems. Table 1 shows the main parameter of the reference power plant used in this study.

Table 1 The main parameter of the reference plant

Parameter	Value
Ambient condition	1.01 bar; 31 C; 0.70 RH
Main steam (MS)	1.246.981 kg/hr; 169 kg/cm2; 540 C
One-stage reheating steam (RH)	1.089.752 kg/hr; 40 kg/cm2; 540 C
Feed water heaters	3 LP heater and 3 HP heater
Exhaust flue gas	145 C
Turbine and generator efficiency	42% and 99%

3.2. LCM Technical Assessment

The technical assessment focuses on the impact of each LCM alternative plan strategy on the efficiency and reliability of the power plant, which are stated as follows:

- Collect the equipment operation parameter data, such as pressure, temperature, flow, gross generator output (GGO), net generator output (NGO), auxiliary power (Aux), etc.
- Collect the maintenance data history, namely date of failure, repair time (RT), downtime (DT), cost of spare part/repair (MCR) or inspection (MCS), labor (CR_{RM}), and the processes that follow the breakdown (C_{pb}), etc.
- Calculate the impact of LCM planning on efficiency. This includes thermal efficiency (η_{TH}), boiler efficiency (η_B), turbine efficiency (η_T), generator efficiency (η_G), gross plant heat rate (GPHR), net plant heat rate (NPHR), etc.
- Calculate the impact of LCM planning on reliability, such as failure, repair distributions, failure rate, mean time between failure (MTBF), mean time to repair (MTTR), mean downtime (MDT), meantime inspection time (MIT), etc.

3.2.1. Efficiency analysis

The coal variation has an impact on the boiler efficiency of the power plant. Moreover, the turbine and generator efficiency remains constant. These efficiencies are directly calculated as follows:

$$\eta_{TH} = \eta_B . \eta_T . \eta_G \tag{1}$$

$$\eta_B = \frac{\dot{m}_{ms}.h_{ms} + \dot{m}_{RHout}.h_{RHout} - \dot{m}_{fw}.h_{fw} - \dot{m}_{RHin}.h_{RHin}}{\dot{m}_C.LHV} \tag{2}$$

where $\dot{m}_{ms}$, $\dot{m}_{RHout}$, $\dot{m}_{fw}$, and $\dot{m}_{RHin}$ are turbine throttle, hot reheat outlet, feed water; hot reheat inlet mass flow rate (kg/h), h_{ms}, h_{RHout}, h_{fw}, and h_{RHin} are turbine throttle; hot reheat out, feed water, and hot reheat inlet enthalpy (kJ/kg); $\dot{m}_C$ is the coal flow rate (kg/h); while LHV is low heating value of coal (kcal/kg). However, other general indicators are gross plant heat rate ($GPHR$) and net heat rate ($NPHR$).

$$GPHR = \frac{\dot{m}_C . LHV}{GGO} \tag{3}$$

$$NPHR = \frac{\dot{m}_C . LHV}{NGO} = \frac{\dot{m}_C . LHV}{GGO - Aux} \tag{4}$$

where GGO, NGO, and Aux are gross generator output, net generator outputs, and auxiliary power (MW), respectively. The operation data history is recorded on distributed control system (DCS). All of the operation data for efficiency analysis was acquired on a monthly basis using the performance test as a standard (ASME, 2013). Therefore, 20 sets of data were acquired for each coal. Table 2 shows the efficiency test data during the research period.

Table 2 Measured operation data during the test

Month	High Rank Coal				Low Rank Coal			
	LHV (kcal/kg)	Coal Flow (t/h)	GGO (MW)	Aux (MW)	HHV (kcal/kg)	Coal Flow (t/h)	GGO (MW)	Aux (MW)
01	4787	194.6	400.0	28.2	4314	225.3	397.0	27.9
02	5112	184.4	405.0	28.8	4091	234.3	391.0	27.4
03	4933	189.3	402.0	27.8	4186	232.4	396.0	29.0
04	5079	185.1	404.0	28.2	4244	228.7	396.5	28.2
05	4888	190.8	401.0	27.7	4113	234.1	394.5	30.0
06	4860	191.3	401.0	27.8	4262	227.8	396.5	28.0
07	4905	189.8	401.5	27.4	4428	220.1	398.0	28.2
08	4902	190.6	401.5	27.6	4392	222.0	397.5	27.8
09	5021	186.9	402.5	28.0	4389	221.9	397.5	28.0
10	4858	191.4	400.5	27.3	3955	238.4	387.0	26.7
11	4979	188.3	402.0	27.7	4052	235.8	391.0	28.5
12	4699	198.3	399.0	27.8	4343	225.1	397.0	27.8
13	4815	193.7	400.0	27.9	4185	231.3	396.0	29.4
14	4980	186.9	402.5	28.1	4171	230.2	395.5	29.4
15	4731	196.1	399.5	28.0	4294	224.4	397.0	28.3
16	5079	184.8	404.5	28.6	4203	229.3	396.0	28.0
17	5047	185.7	403.5	28.3	4049	233.9	389.0	26.8
18	4927	189.5	401.5	27.3	4314	226.0	397.0	27.8
19	4833	191.5	400.5	28.2	4177	231.5	396.0	29.5
20	4905	189.7	401.5	27.3	4230	227.5	396.0	28.0
Ave.	4917	189.9	401.6	27.9	4220	229.1	395.1	28.2

3.2.2. Reliability analysis

Coal variation would influence a power plant failure rate and its reliability, especially on the boiler directly related to the coal process. In this study, the failure distribution is assumed to follow a repairable system. This simply means that, whenever the equipment fails, it needs to be repaired rather than replaced. It is not a perfect repair; it is a minimal repair. Failure distribution of the repairable system is based on a power-law or nonhomogeneous poison process (NHPP). The failure intensity ($\rho(t)$) and the expected number of failure ($E[N(t)]$) for the power-law process is calculated as follows:

$$\rho(t) = \lambda \beta t^{\beta - 1} = \frac{1}{\theta^{\beta}} \beta t^{\beta - 1} \tag{5}$$

$$E[N(t)] = \int_0^t \lambda(t) dt = \lambda t^{\beta} \tag{6}$$

where λ, β, and θ are lambda, beta, and eta parameters, respectively.
The reliability ($R(t)$) and cumulative mean time between failures (MTBF) are also calculated as follows:

$$R(t) = e^{-[\lambda(t+d)^{\beta} - \lambda t^{\beta}]} \tag{7}$$

$$MTBF = \frac{1}{\lambda} T^{1-\beta} \tag{8}$$

where t and d are a system of age and mission length, respectively. Subsequently, whenever the equipment fails, it migrates into the repair process. However, repair time (RT) is treated as a random variable. Several factors cause it, such as different failure modes, components, and causes. The mean time to repair (MTTR) tends to be determined from repair distribution. Apparently, during the repair period, the equipment is presumed to be down. Commonly, equipment downtime (DT) is greater than the repair time (RT) due to delays. As a consequence, the cost rises, assuming there is no backup (redundancy). Repair time and downtime distribution are assumed to follow the Weibull distribution. The cumulative repair distribution function ($H(t)$) and MTTR, in accordance with Weibull distribution, is reported as follows:

$$H(t) = 1 - e^{-\left(\frac{t}{\theta}\right)^{\beta}} \tag{9}$$

$$MTTR = \theta . \Gamma \left(1 + \frac{1}{\beta}\right) \tag{10}$$

where Γ is the gamma function. In addition, Equations 9 and 10 are also used to calculate DT distribution and MDT. Reliability analysis is carried out for every single failure at the equipment level throughout the entire research period and was further aggregated at the system or plant level. All maintenance data history is recorded in the computerized maintenance management system (CMMS). Tables 3 and 4 show the historical maintenance data of the furnace system and the air and gas system when using the HRC.

Table 3 Failure and repair data for furnace system when using HRC

No	TTF (d)	RT (h)	DT (h)	MCS (USD)	C_{pb} (USD)	Problem
01	16	2	3	434	0	Coal feeder 1D failure
02	72	6	6	0	2.980	Seal mill 1B failure
03	94	3	4	0	1.206	Mill 1D scrapper failure
04	107	10	20	1.642	46.434	Mill 1C motor failure
05	109	2	3	0	0	Mill 1D strainer DP high
06	127	6	8	0	4.103	Coal feeder 1C failure
07	154	1	2	0	0	Coal feeder 1A failure
08	173	4	4	0	1.446	Mill 1B grinder failure
09	228	6	8	0	5.913	Coal feeder 1A belt slipped
10	241	1	2	0	2.542	Mill 1D scrapper failure
11	288	16	96	13.471	304.044	Mill 2E valve seal failure
12	309	4	6	0	2.788	Mill 1A motor vibration
13	312	4	6	0	3.312	Mill 1E grinding roll failure
14	359	2	3	0	0	Mill 1D motor temp. high
15	363	9	14	827	10.659	Mill 1A lube oil failure
16	421	2	2	0	0	Coal feeder 1D failure
17	485	12	20	2.411	68.015	Mill 1D inboard temp. high
18	500	2	3	0	0	Mill 1E fail start
19	510	3	4	0	428	Mill 1B lube oil failure
20	531	8	14	595	6.682	Coal feeder 1B failure

Table 4 Failure and repair data for air and gas system when using HRC

No	TTF (d)	RT (h)	DT (h)	MCS (USD)	C_{pb} (USD)	Failure Description
01	30	1	2	2.214	15.159	PAF 1B trip
02	59	1	3	425	0	PAH 1A bearing failure
03	98	2	3	0	0	PAF 1B bearing temp. high
04	123	2	3	0	0	FDF 1A damper failure
05	175	2	4	891	0	PAF 1A motor failure
06	220	3	4	0	0	SAH 1A air drive failure
07	233	3	4	0	0	IDF 1B RPM hunting
08	234	3	5	0	0	PAF 1A bearing temp. high
09	240	4	5	811	0	PAF 1A vibration high
10	247	4	6	690	0	PAF 1A vibration high
11	260	4	6	629	0	FDF 1A motor failure
12	268	4	6	2.060	0	PAF 1A bearing failure
13	282	6	6	0	0	PAF 1A oil pump failure
14	288	6	8	679	0	IDF 1B turning gear failure
15	320	6	8	690	0	IDF 1B bearing failure
16	330	6	8	0	0	IDF 1A motor failure
17	371	6	8	0	0	IDF 1B gate failure
18	428	6	8	0	137	SAH steam coil line failure
19	468	6	8	14.379	0	IDF 1B damper failure
20	520	8	10	0	0	SAH 1A damper failure
21	524	8	10	2.228	0	PAH 1A bearing failure
22	595	12	12	0	0	SAH 1B damper failure

Tables 5 and 6 show the historical maintenance data of the furnace system and the air and gas system when using the LRC.

Table 5 Failure and repair data for furnace system when using LRC

No	TTF (d)	RT (h)	DT (h)	MCS (USD)	C_{pb} (USD)	Failure Description
01	12	2	2	0	3,957,442	Mill 1E coal pipe failure
02	77	2	2	3,551,184	1,277,654	Mill 1B lube oil failure
03	83	3	2	0	5,202,233	Mill 1C bearing failure
04	90	3	2	2,118,000	0	Mill 1A oil mill leaks
05	140	20	105	154,998,418	9,315,423,333	Wall tube failure
06	168	6	9	0	9,267,889	Mill 1D gear box failure
07	174	10	14	0	0	Mill 1A inner part failure
08	228	6	6	0	3,824,000	Mill 1B lube oil pump failure
09	230	4	4	0	2,740,533	Mil 1D lube oil failure
10	236	4	4	8,359,092	1,530,397	Mill 1B lube oil failure
11	243	4	4	1,059,000	0	Mill 1D inert trap failure
12	249	4	6	0	2,469,667	Mill 1C isolation valve failure
13	262	6	6	5,000,000	0	Mill 1D filter oil failure
14	270	20	28	76,271,647	754,870,546	SH tube temperature hunting
15	276	6	8	0	0	Mill 1D journal shaft failure
16	293	6	8	0	0	Mill 1A pyrites hopper failure
17	319	6	8	0	6,978,800	CV RH spray failure
18	322	3	3	0	0	Mill 1A dynamic class failure
19	341	8	9	0	1,951,833	Mill 1A seal air fan failure
20	350	8	9	0	1,673,000	Mill 1E coal pipe failure
21	405	8	9	0	0	Mill 1B gland packing failure
22	438	10	14	0	0	Mill 1D CV inert steam failure
23	466	3	3	0	0	Mill 1D lube oil failure
24	504	10	28	0	0	Mill 1B valve failure
25	542	3	2	50,529,500	0	Mill 1D body failure
26	597	3	3	0	0	Mill 1B scrapper failure

Table 6 Failure and repair data for air and gas system when using LRC

No	TTF (d)	RT (h)	DT (h)	MCS (USD)	C_{pb} (USD)	Failure Description
01	40	1	2	1,200,000	0	PAH 1H motor temp high
02	48	1	2	81,260,000	0	PAF 1B tie rod failure
03	60	2	3	0	0	PAF 1A tie rod failure
04	91	3	3	16,272,000	0	PAF 1A motor failure
05	99	3	4	189,860,000	0	IDF 1B head coupling failure
06	125	10	12	0	1,912,000	FDF 1A chasing duct failure
07	145	12	14	3,500,000	213,626,167	PAH 1A air out temp hunting
08	160	6	8	0	0	SAH 1A steam coil SAH 1A
09	175	8	8	45,028,067	0	IDF 1B O2 analyzer failure
10	187	4	6	81,200,000	59,637,833	SAH 1A damper failure
11	217	4	6	0	0	PAF 1A oil bearing failure
12	272	6	6	0	0	PAH 1B air drive failure
13	283	6	6	23,512,500	0	PAF 1A oil failure
14	298	6	6	0	0	PAF 1B line duct failure
15	301	6	6	0	0	PAF 1B air temp. failure
16	315	6	6	0	8,057,850	IDF 1B motor vibration
17	340	6	6	1,248,500	0	PAF 1A tie rod failure
18	353	6	6	11,352,000	0	FDF 1A lube oil pump failure
19	374	6	8	0	0	PAF 1A motor vibration
20	381	3	4	7,837,500	0	PAF 1A oil failure
21	388	4	6	0	0	IDF 1B O2 analyzer failure
22	406	6	8	2,450,000	0	PAF 1A bearing temp. high
23	410	6	8	0	0	PAH 1A air inlet temp failure
24	420	6	8	72,735,828	0	SAH 1A motor failure
25	444	3	4	0	0	PAF 1B bearing vibration
26	467	3	4	0	0	SAH 1A Switch failure
27	536	6	8	0	0	SAH 1B steam coil failure
28	543	6	8	13,528,640	0	PAF 1A tie rod failure

The availability of the system (A) could be calculated as follow:

$$A = \frac{MTBF}{MTBF+MDT} \tag{11}$$

Where A is operation availability (%). The availability for series and parallel systems could be calculated as follow:

$$A_s = \prod_{i=1}^{n} A_i \tag{12}$$

$$A_p = 1 - \prod_{i=1}^{n} (1 - A_i) \tag{13}$$

Where As, Ap and Ai are the availability of the series system, availability of parallel system and availability of individual components. Equations 12 and 13 also could be used to calculate the reliability of series and parallel systems.

3.3. LCM Financial Assessment

Any change in the technical parameters, whether reliability or efficiency, has an impact on the financial parameter at a certain significance level. The financial parameters analyzed are the total cost, revenue, and profit of the power plant, which are reported as follows:

- Collect all data related to the financial parameter, namely acquisition date, cost, fuel, spare parts, labor, consequence, electricity costs, etc.
- Calculate the total cost, revenue, profit, and equivalent annualized cost (EAC)
- Define the optimum LCM plan strategies based on the maximum profit
- Obtain the best decision to determine whether a capital intervention needs to be maintained, rehabilitated, or demolished

3.3.1. Cost analysis

The total cost of a power plant is the sum of the acquisition, fuel, operation, maintenance, and disposal costs. It is calculated as follows:

$$TC(t) = C_i + \sum_{i=1}^{T} \frac{(F_t + O_t + M_t)}{(1+d)^t} + C_d \tag{14}$$

where $TC(t)$ is the total cost of a power plant during t year, C_i is acquisition cost, C_d is disposal cost, F_t is fuel cost, O_t is operation cost, and M_t is the maintenance cost for the year t (Rp), while d is the discount rate (%). The fuel cost (F_t) and the operation cost (O_t) in a year are calculated as follows:

$$F_t = \frac{86750.NPHR.NGO.CF.C_f}{LHV} \tag{15}$$

$$O_t = O_C.T \tag{16}$$

where CF is capacity factor (%), C_f is fuel unit cost (USD/kg), O_C is labor unit cost (USD/year), and T is time (year).

The maintenance cost (M_t) is calculated as follows:

$$M_t = M_R + M_I \tag{17}$$

where M_R is repair cost and M_I is inspection cost (USD/year). The repair and maintenance costs are calculated as follows:

$$M_R = \left[MCR + CR_{RM}.MTTR + C_{pb}.MDT\right].E[N(t)] \tag{18}$$

$$M_I = \left[MCS + (CR_{RM}. + C_{pb}).MIT\right].n.T \tag{19}$$

where MCR is the spare part cost per failure, MCS is the spare part cost per inspection (USD/Inspection), CR_{RM} is labor cost (USD/h), and C_{pb} is process cost following repair or inspection period (USD/repair or USD/inspection). Furthermore, n is the number of inspections in a year. The spare part and process costs vary randomly. The average value of the historical data was used for the estimation process. In this case study, the acquisition cost is constant and the disposal costs are negligible.

3.3.2. Revenue analysis

The revenue of the power plant depends on CF and is calculated as follows:

$$TR(t) = 8750.NGO.CF.C_e.T \tag{20}$$

where $TR(t)$ is the total revenue during t year (USD) and C_e is the electricity price (USD/kWh).

3.3.3. Profit analysis

The total profit of the power plant is calculated as follows:

$$TP(t) = TR(t) - TC(t) \tag{21}$$

where $TP(t)$ is the total profit of a power plant during t year (USD). The power plant was unable to earn a profit in the early operational period due to the high acquisition cost in the first year. It is expected to continue before the break-even point (BEP), where the total cost is equivalent to the revenue. The minimum CF to get BEP (CF_{BEP}) could be found by substituting Equation 11 to Equation 17.

$$CF_{BEP} = \frac{C_i + \sum_{i=1}^{T} \frac{(F_t + O_t + M_t)}{(1+d)^t} + C_d}{8750.NGO.T.C_e} \tag{22}$$

Based on Equation 19, the plant has to operate at a CF above CF_{BEP} in order to generate the profit. Otherwise, it would not be viable.

3.3.4. Optimization analysis

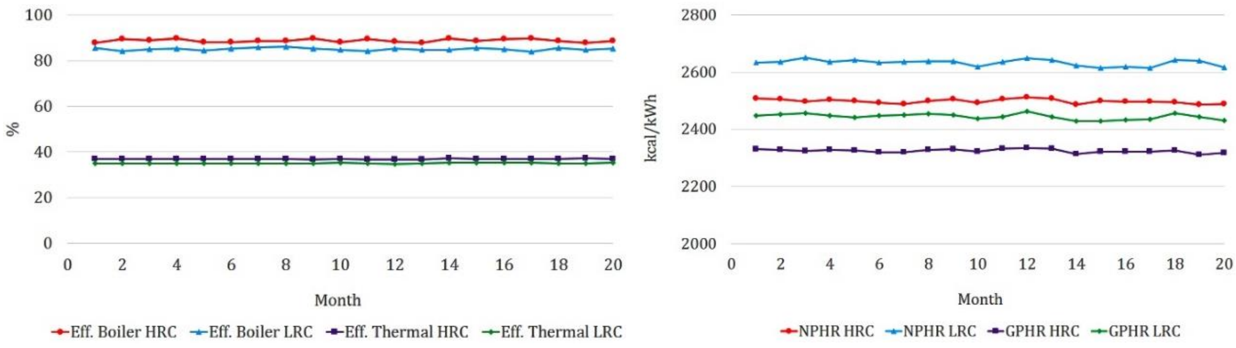
The ultimate process of LCM is to select which of the alternative planning strategies is optimum. The net present value (NPV) was used to compare each alternative, especially when the project evaluation period is already defined. In some cases, the period of evaluation is regarded as a variable. Additionally, the equivalent annual cost (EAC) is more suitable than NPV in the case of replacement analysis or capital intervention. The EAC is the annual cost of owning, operating, and maintaining an asset throughout its entire lifespan. The EAC is NPV divided by the "present value of annuity factor" (At,r):

$$EAC = \frac{NPV}{A_{t,r}} = \frac{\sum_{t=1}^{t=n}\frac{F}{(1+d)^t}}{\frac{1-\frac{1}{(1+d)^t}}{d}} \tag{23}$$

where F is the future value for a given period.

4. Results and Discussion

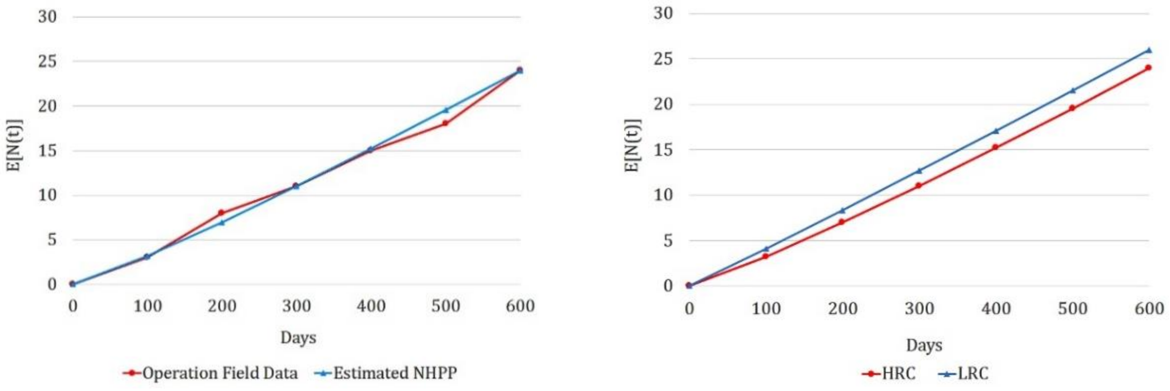
Figure 4a shows the boiler and thermal efficiency of the power plant using HRC and LRC bases on Equations 1 and 2. The average boiler efficiency and thermal efficiency using HRC are 88.81% and 36.99%. These efficiencies were higher than using LRC, where the boiler efficiency is 85.06%, and thermal efficiency is 35.18%. The use of LRC caused a decrease in both variables. The LRC moisture content is higher than the HRC. Switching the coal from HRC to LRC reduces the boiler efficiency (η_B) and thermal efficiency (η_{TH}). This phenomenon occurred due to more enthalpy losses from flue gas exhaust. Lowering the coal heating value also causes an increase in the auxiliary power (pulverizer, fans, and air heater) due to the excessive coal, air, and gas flow required at the same generator load. Additionally, it also causes a decrease in net energy. The use of LRC rather than HRC led to an increase in GPHR and NPHR (Figure 4b).



(a) (b)

Figure 4 The impact of coal switching to: (a) Efficiency; and (b) Heat rate

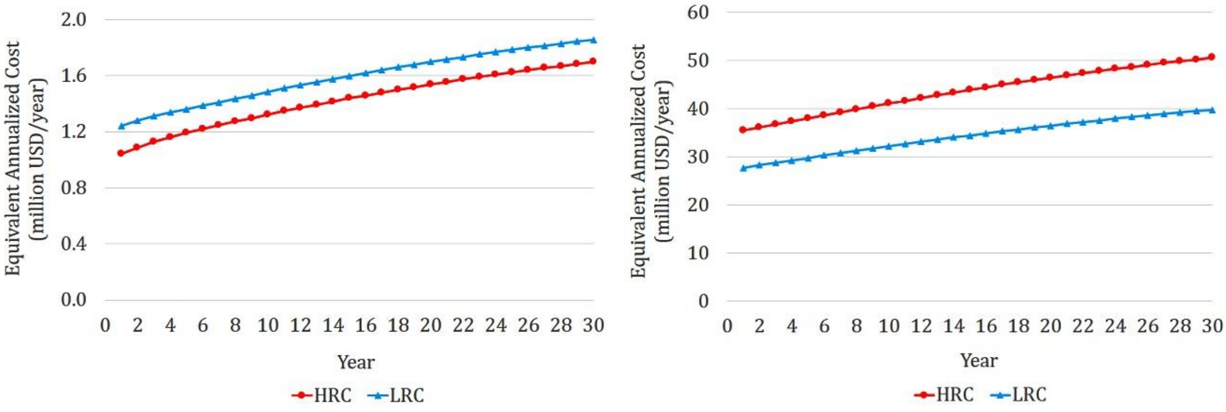
The alteration of coal properties has an impact on their reliability. Equations 5 and 6 could be used to find out its impact on the failure intensity and the number of failures of equipment. Figure 5a shows the number of furnace system failures (E[N(t)]) while using HRC from the field data history (Table 3) to estimate the NHPP parameters. The two curves are similar, meaning that NHPP is accurate to estimate the field data history. The result also shows that the number of furnace system failures using HRC to estimate NHPP parameters was lower than LRC (Figure 5b). This means that the equipment is more reliable when using HRC compared to LRC. Based on Equation 7, the reliability when using HRC and LRC was 26.08% and 25.80%, respectively. The reliability when using HRC is higher than LRC due to a higher failure of LRC. It causes the MTBF of HRC to also be higher. The MTBF, obtained using HRC and LRC, were 25.00 and 23.08 days, respectively. The mill is a piece of equipment that contributes to the failure rate whenever the LRC is used (Table 3).



(a) (b)

Figure 5 The cumulative number of failures: (a) Field data vs. Estimated; and (b) HRC vs. LRC

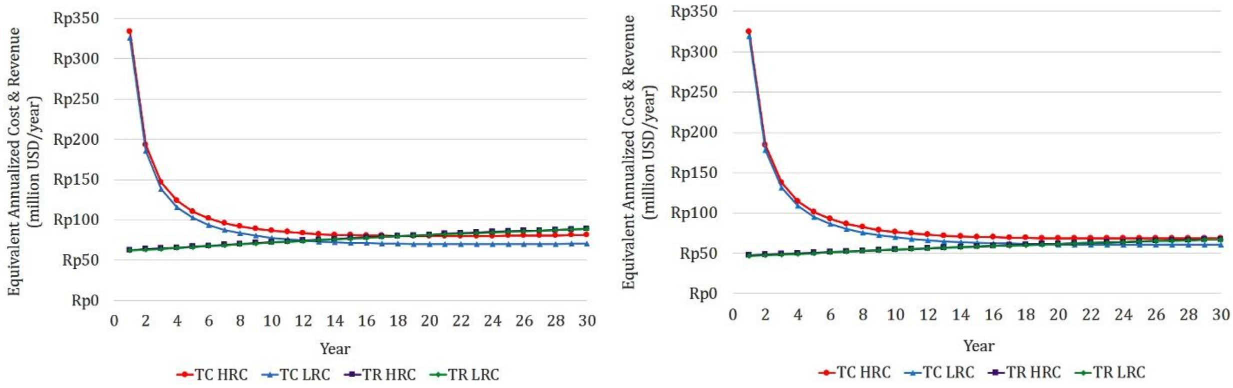
Additionally, this occurs due to plugging or excessive load. The LRC has more tendencies to cause plugging or excessive load compared to the HRC due to higher moisture, smaller size, and lower calories. A similar result occurred in the air and gas system when LRC was used compared to the HRC. The air and gas the boiler required are higher when the LRC was utilized. The reliability of the air and gas systems when using HRC and LRC were 30.37% and 23.23%, respectively. The MTBF using HRC and LRC were 27.27 and 21.43 days, respectively. The lower MTBF when using LRC was due to an excessive load. This was extensively discovered in the primary air fan/PAF (Table 4). The PAF has to supply more air for coal transportation and drying due to lower calories and higher moisture when using the LRC. The MTTR and MDT of the boiler, air, and flue gas systems were higher when the LRC was used than the HRC, although the difference was insignificant. The reliability of the plant is 7.83% when use HRC and 6.06% if use LRC. The availability of the plant when use HRC is 97.93%. It is higher than LRC that is 97.45%. The plant has higher availability when using HRC than LRC due to higher reliability, higher MTBF and lower MDT. The LRC has a higher annualized maintenance cost than the HRC due to the increased failure rate, as shown in Figure 6a. But the LRC has a lower annualized fuel cost because the reduction in the unit fuel cost when LRC was used compared to the HRC is much higher than the increased fuel consumption, as shown in Figure 6b. The annualized operation cost for HRC and LRC are relatively similar because both downtimes differ slightly. Overall, in terms of the total cost, the LRC is lower compared to the HRC because the decreasing fuel cost is higher than increasing its maintenance costs.



(a) (b)

Figure 6 The impact of coal switching: (a) Maintenance cost; and (b) Fuel cost

Based on Equation 20, the revenue of the power plant depends on the load CF. Figure 7a shows that the revenue is based on the first scenario, indicating the fact that the CF and discount rate (d) are 79.46% and 10%, respectively. The annualized revenue is almost similar for both the HRC and LRC. The minimum cost of HRC (79.81 million USD/year) was higher than the LRC (69.83 million USD/year). However, this occurs due to the high total cost of power plants for HRC than LRC. The BEP period of HRC (18.1 years) was realized to be longer than LRC (12.2 years). The annualized profit for LRC in the 30th year was 18.31 million USD/year. It is better than the HRC realized at 7.80 million USD/year.



(a)

(b)

Figure 7 The financial performance at: (a) First scenario, CF_{PRED} of 79.49%; and (b) Second scenario, CF_{PRED} of 60.96%

Conversely, there was a difference of 10.51 million USD/year. Based on this analysis and results, it was concluded that the LRC performs much better in terms of O&M total cost, BEP, and also profit gain realized by the power plant compared to the HRC. In terms of environmental impact, HRC was better than LRC because, in the same load, the boiler has burned less coal when using HRC, so it has produced less CO_2. In the second scenario, the CF was predicted at 60.96% (CF_{PRED}). Furthermore, CF_{PRED} is used to accommodate the changing market demand during the operation period. It is an externally uncontrollable factor that is sometimes different compared to the feasibility study. Figure 7b shows the equivalent annualized cost and revenue at the CF of 60.96%. In this scenario, the BEP for LRC is 19.4 years, and the annualized profit is 6.48 million USD/year in the 30th year. It simply means that when the power plant uses LRC, there is a need to continuously execute similar operations and maintenance strategies.

However, this case is slightly different when HRC is used. The minimum CF_{BEP} for HRC and LRC, as calculated in Equation 19, are 63.83% and 50.82%, respectively. When using HRC, CF_{BEP} was higher than CF_{PRED}, so it could not achieve BEP. The annualized profit is -1.43 million USD/year in the 30th year. Based on this number, the power plant needs to be rehabilitated or rejuvenated whenever it wishes to use HRC rather than LRC. The rehabilitation or rejuvenation is only viable if the annualized profit could be increased again, as expected. Relocating to an area where the cost of electricity is less sensitive is another option to consider if using HRC. A summary of the decision of the two alternative scenarios of coal (LRC and HRC) and CF (CF_{PRED} of 79.46% and 60.96%) are depicted in Table 7.

Table 7 Decision parameter summary of the power plant under investigation

No	LHV (kcal/kg)	η_B (%)	η_{TH} (%)	R (%)	A (%)	CF_{BEP} (%)	CF_{PRED} = 79.46% Decision	CF_{PRED} = 60.96% Decision
1	4.917	88.81	36.99	7.83	97.93	63.83	Continuously operated	Continuously operated
2	4.220	85.06	35.18	6.06	97.45	50.82	Continuously operated	Rehabilitated / Relocated

5. Conclusions

The proposed HOME concept has been proved to fulfil the gap of the previous LCM framework. It comprehensively combines all of the technical and financial analyses needed to support the decisions of the power plant owner, whether it needs to be kept, rejuvenated, or demolished for good. A combined analysis of efficiency and reliability is realized through any change in fuel, operation, or maintenance strategies. The impact on cost and revenue tends to be simultaneously analyzed. The case of fuel changing strategies (HRC and LRC), studied and reported in this research, shows that the HOME frameworks are proven to aid in deciding what to do with the power plant under investigation. It is also capable of predicting the future impact of the external factors on the revenue. The optimum decision concerning whether the power plant needs to be continuously operated, rejuvenated, or demolished, has to be analyzed. The HOME project aids the power plants in simulating and predicting the possibility of all strategic options during its operational period. In addition, the power plant also needs to avoid unnecessary maintenance or rejuvenation, or rehabilitation activities by taking the appropriate decision towards the end of its life cycle. The implementation of the advanced and future power plant technology is easily evaluated and justified. In the case study analyzed in this paper, if it only takes into consideration reliability and efficiency, the power plant under investigation will have to use HRC. The higher the calorific value, the higher its reliability and efficiency. Unfortunately, as it has been simulated and analyzed, those two factors are not enough to justify the viability of the coal calorific values to be used. The other factor that has to consider is the total cost. The total cost will impact the minimum CF to reach the break-even point (CF_{BEP}). Combining those three factors (reliability, efficiency, and CF_{BEP}) into the analysis as suggested by the HOME framework, provides the best decision for all aspects of the power plant, such as operation maintenance, cost, and revenue. Based on Table 5, HRC and LRC could be used if the power plant has a CF_{PRED} of 79.46%. The efficiency and reliability would decrease and generate more carbon emission when using LRC. It needs more expensive maintenance, but produces more profit than HRC. If the CF_{PRED} reduces to 60.96%, then only the LRC is viable. Rehabilitation or rejuvenation must occur when using LRC. Based on the case study, the HOME framework was extremely effective and used to make the best decision concerning the power plant under investigation. This is necessary in order to remain competitive in an uncertain electricity market and business condition. It effectively guides the power plant operation and maintenance by providing the best decision at every stage (age). However, integrating and directly linking it to the power plant database, such as the DCS and the CMMS for operational and maintenance data, provides a dynamic and simultaneous analysis of the current position of the performance and prediction. This saves a lot of time and money and ensures the power plant is always a competitive edge in terms of the cost of electricity generated and, even more important, in the current VUCA condition. In this case study, the acquisition cost is constant. On the contrary, the disposal cost is negligible. In certain circumstances, such as asset reevaluation or divestment, the acquisition and disposal costs were very important to consider. It has a significant impact on the total cost and parameters that to consider for future research.

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