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The Assessment of Electrical Energy Management through Case Study in Coal Handling System of Coal-Fired Power Plant

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ABSTRACT

Coal Handling System (CHS) is the main system of Coal Fired Power Plant (CFPP), managing coal transportation from Vessel by Ship Unloader to coal yard through belt conveyor (BC) and Stacker/Reclaimer (S/R), then transported to Silo, known as forwarding process. CHS involves various large electric motors. The unwisdom of operating motors would result in wasteful electrical energy consumption. To assess the energy management, United Nations Industrial Development Organization (UNIDO) provides Energy Management System (EnMS) tools based on ISO 50001 industrial sectors. This tool identifies that operational patterns and maintenance activities have a significant impact on the energy consumption. Technically using Integrated SKF Calculation, applying the scenario of direct replacement conveyor rollers age more than 2 years by only 30%, saves 103,144.20 kWH per cycle, equal to IDR 102,807,951, rather than replacing rollers when broken only. Meanwhile, Lean Six Sigma concept on increasing cycle performance, could save a monthly 594,984 kWH, equal to IDR 593,044,189.

ABSTRAK

Coal Handling System (CHS) adalah sistem utama PLTU yang mengatur pengangkutan batubara dari Vessel dengan Ship Unloader ke coal yard melalui belt conveyor (BC) dan Stacker/Reclaimer (S/R), selanjutnya diangkut ke Silo, yang dikenal sebagai proses *forwarding*. CHS melibatkan berbagai motor listrik berdaya besar. Ketidakbijaksanaan dalam mengoperasikan motor-motor ini mengakibatkan konsumsi energi listrik menjadi boros. Untuk mengevaluasi pengelolaan energi, *United Nations Industrial Development Organization* (UNIDO) menyediakan pedoman Sistem Manajemen Energy (SME) berdasarkan ISO 50001 pada sektor industri. Pedoman ini mengidentifikasi bahwa pola operasional dan aktivitas pemeliharaan mempunyai dampak signifikan terhadap konsumsi energi. Secara teknis menggunakan *Integrated SKF Calculation*, penerapan skenario penggantian langsung roller conveyor yang berumur lebih dari 2 tahun sebesar 30% saja, menghemat 103.144,20 kWH per siklus, setara IDR 102.807.951, dibandingkan mengganti roller saat rusak saja. Sedangkan konsep Lean Six Sigma pada peningkatan kinerja siklus operasional, dapat menghemat 594,984 kWH setiap bulannya, setara IDR 593.044.189.

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INTRODUCTION

In a few decades, belt conveyor (BC) system has played a role as the main transportation equipment for coal handling. Currently, most BCs are operated in fixed speed mode, although the production process does not run continuously, resulting in no-load or half-load operational conditions, which means experiencing low-efficiency conditions (Mu et al., 2020). A lot of research and application of variable speed drive (VSD) technology has been applied to BC systems, where the conveyor speed can be adjusted as necessary, which could save power consumption (Zeng et al., 2015). Apart from saving energy, the maintenance costs shall be lower with VSD technology. However, the field study facts show that majority of electrical motors still use the Direct Online (DOL) system (Kucuk & Ajder, 2022), because the investment costs are much lower than VSD. Therefore, other methods are suggested in terms of energy efficiency on the existing system.

The United Nations Industrial Development Organization (UNIDO), an organization overseeing the development of sustainable industry in the world, has launched program related to Energy Management Systems (EnMS) based on ISO 50001 (Arthur, 2021). The objective is to provide a framework and tools for assessing and developing EnMS, thereby supporting identifying energy savings opportunities, reducing greenhouse gas (GHG) emissions, and improving sustainable energy performance. EnMS uses the basic concept of Plan, Do, Check, Action (PDCA), a management model introduced by Walter Shewhart (Donovan, 2014). In EnMS planning step, there are eight Energy Review (ER) activities to identify the energy system performance and provide opportunities for improvement.

Pulley and Roller, as the main part of BC system, contain bearings to rotate as its function (Vasić et al., 2020). The bearing will encounter direct load imposed by coal transportation. Introducing *Integrated SKF Calculation*, a web-based tool from SKF as the leading bearing product manufacturing companiy, allowing users to compute various bearing calculations, such as rating life, minimum load, friction, power loss, energy consumption in a certain period, etc. This calculation can be processed simply by entering bearing type, radial load, axial load, rotational speed, and bearing temperature. Other supplement data for calculation are general assumptions according to SKF's standards.

Besides improving energy performance technically, energy savings can also be reviewed at operational level or perspective of management. One concept that could be applied is Lean Six Sigma (LSS). LSS is a comprehensive attempt carried out by company to improve business performance, focusing on quality, costs, investment, and acceleration or short cycle time (Rathi et al., 2022). To find out activities that do not provide profit value, mapping is drawn from historical data in a certain period. Concerning energy-saving endeavors, value-added, non-value-added but necessary, and non-value-added activities might not always have a direct impact on reducing energy consumption (Aughney & O'Donnell, 2015). However, it might be predicted by looking for the average duration of each job, and comparing it to ideal duration based on discussion forums, and finally looking for opportunities of effective duration. As a result, the several activities that consume large energy shall be decreased along with less operational duration. The application of LSS consists of five main phases, usually called DMAIC which represent the initial letters of each activity (Kowang et al., 2022). Define and Measure is determining problem to be sought and how to collect it. Analyze and Improve is identifying the wastes and steps to reduce them. Control is a management step further until the establishment of a new Working Instruction (WI), including evaluation of whether or not the implemented program is effective. Since conveyor system consumes the highest electrical energy, efficiency program scenarios shall be applied within it by applying guidance from UNIDO, SKF calculations, and LSS concept.

RESEARCH METHODS

To assess energy management, it is essential to acknowledge overall energy performance of CHS equipment in the past years, looking for the relationship between maintenance activities and energy consumption, calculating energy consumption of BC components, as well loaded motors to verify data calculation and actual.

Calculation of Historical Data from Graphs

Many companies do not apply kWH-meter for each electrical motor. Therefore, to see historical kWH data is by exporting graph data and calculating in trapezoidal numerical method (Chapra & Canale, 2015) to find current value (I), as follows:

$$I = \frac{(b-a)}{2}(f(a) + f(b)) \quad (1)$$

The energy consumption of 3 phases connection shall be calculated for period of time (t), at a constant voltage (V) and power factor (Cos θ):

$$kWH = \sqrt{3} x\ V\ x\ I\ x\ Cos\ \theta\ x\ t \quad (2)$$

Regression Analysis

The changes in energy consumption can be affected by various factors (drivers). These drivers might from various existing protection systems on equipment, operating behavior, and maintenance activities. To determine the relationship between drivers and energy consumption, regression analysis is applied with analysis of variance (ANOVA) as the following formulation (Montgomery et al., 2015):

$$Y = aX + b \quad (3)$$

where Y = energy consumption (kWh), X = number of drivers, a = gradient, b = intercept. In this research, maintenance will be used as a driver variable.

Radial Load on Roller

Each roller of BC system encounters load weights and radial loads (Kuvandikov et al., 2021), according to the Equation (4) below:

$$Q = 3.6 * q * V \quad (4)$$

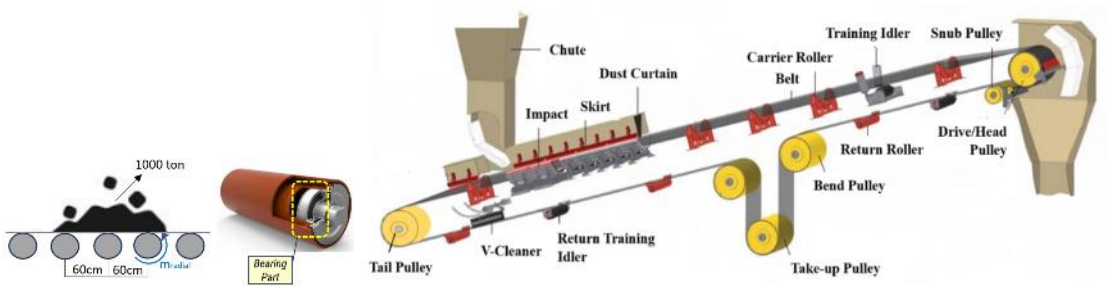
where Q = conveyor capacity (tph or kg/s), q = load weight per m (kg/m), v = conveyor speed (m/s), g = gravitational force (m/s²) which is known 9.81. Then the radial load (m_{radial}) is calculated using the equilibrium equation (Xiaoli et al., 2017) ΣMa = 0, getting:

$$m_{radial} = \frac{q*60}{120} \quad (5)$$

Radial load encountered by roller, shown in Figure 1(a), is also a burden to roller bearings inside. The greater BC capacity, the greater radial force and energy required to rotate rollers.

Radial Load on Pulley

There are several types of BC pulleys as seen in Figure 1(b), such as drive pulley, installed by motor and gearbox set, head-tail pulley at BC both edges, take-up pulley as a weight system to keep the belt tensioning properly as per increasing age (Li et al., 2017). Whereas bend and snub pulley are located in the intersection to keep belt stable in proper position. Each BC pulley has a maximum tension specification based on manufacturing. However, in a real application, pulley is given a tension below its maximum tension, according to the engineering calculations. The greater tension encountered by pulley, the greater energy consumption required to rotate pulley. The radial force is encountered by both pulley and bearing.



(a) **(b)**

Figure 1. (a) Illustration rollers loaded by coal; (b) Belt Conveyor System
(Source: Beijing Qizhantrieng Engineering Technology Co., Ltd)

Electrical Motor Energy Consumption

To calculate the energy consumption of motor, constant parameters are required for BC system loading, as follows (Kulinowski & Kasza, 2014):

- Material Weight

$$Wm = \frac{Q}{V} \quad (6)$$

- Belt Weight

Belt weight generally corresponds to the belt width itself and follows the Rulmeca Vendor Catalogue which is currently used on-site (RULMECA, n.d.).

- Effective Tensile Force

When operating, head/drive pulley will get the driving force from the drive system to pull BC. Theoretically effective tensile force shall be calculated based on the Eq (7).

$$Fe = Wm * H + 0.04(2 * Wb + Wm) * L \quad (7)$$

where Fe = effective tensile force (N), H = height difference between head and tail pulley (m), L = material transfer distance (m).

- The Required Motor Power

Based on the effective pulling force on conveyor, the minimum power required for motor to operate at a certain load is in (RULMECA, n.d.) Eq (8). While motor nameplate capacity used to be larger for safety factors as Eq (9):

$$P = Fe * V \quad (8)$$

$$Pm = \frac{P_t}{\eta} \quad (9)$$

where P = motor power (W), Pm = maximum motor power, η = efficiency, generally at 0.85

- Payback Period Cost Analysis

One common method cost analysis is Simple Payback Period (SPP). SPP determines the number of periods required to recover the initial investment costs through a project. The formula is in (Lepkova et al., 2014) Eq (10):

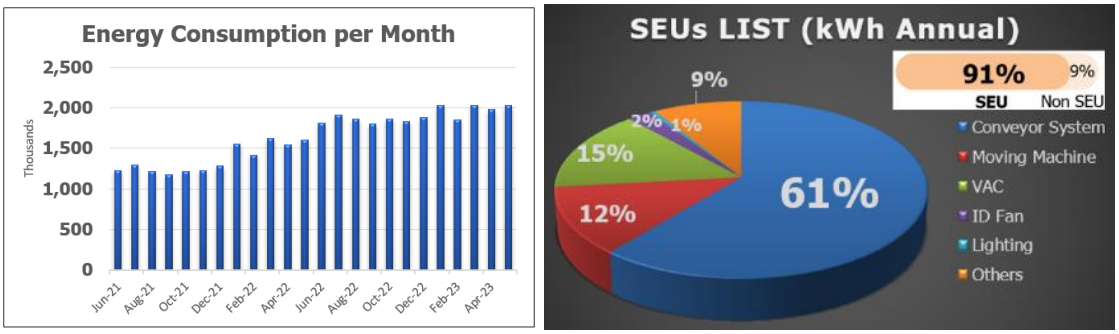
$$SPP = \frac{\text{Initial Investment}}{\text{Periodic Savings}} \quad (10)$$

RESULTS AND DISCUSSION

Energy Consumption in Coal Handling Systems

The energy consumption historical data in the last two years was extracted from the CHS-HMI Jawa 4 CFPP from June 2021 to May 2023. By using a trapezoid area formula to read the

graph extracted in tabular, the energy consumption per month is in graphic Figure 2(a). Following Energy Review steps from UNIDO tool, the energy consumption increases along with the Main Unit operations. The equipment is then grouped as Significant Energy Users (SEUs) in a pie diagram Figure 2(b), shows that of 91% SEUs, 61% come from Conveyor System.

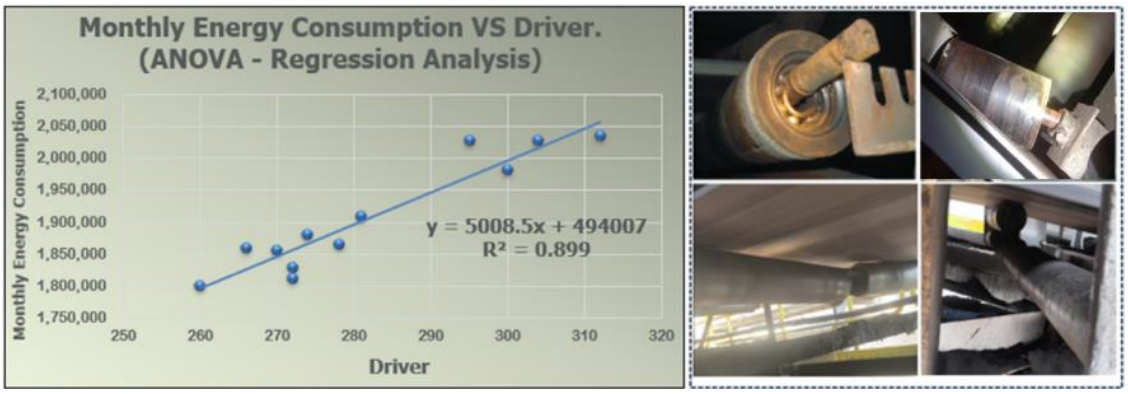


(a) (b)

Figure 2. (a) Coal Handling System Monthly Energy Consumption; (b) Pie Diagram of SEUs

Maintenance activities and Energy Consumption

To determine the maintenance activities' effect on energy consumption patterns, an ANOVA analysis is applied for a year-based period. Corrective Maintenance (CM) which stops CHS operations and requires testing after finished is considered. Figure 3(a) shows the regression equation of $y = 5{,}008x + 494{,}007$. R^2 is the determination coefficient indicating the equivalency level of model, which is precision as it gets closer to 1. A slope value of 5,008.5 represents the incremental energy consumption per maintenance activities, and 494,007 depicts the estimation of fixed energy consumption. This leads to the conclusion that the more maintenance activities, the higher energy requirements. Figure 3(b) shows the frequent roller trouble, including CM.



(a) (b)

Figure 3. (a) Regression Analysis of Maintenance vs Energy Consumption; (b) Roller Damage

Table 1. CHS Corrective Maintenance percentage for a year

Problem Category	Amount	%
Cleaner	171	12
Hose	24	2
Leakage	141	10
Miss/Loosen Bolt	283	20
Pulley	77	6
Roller	**429**	**31**
Rubber	185	13
Scrapper	75	6

CM's total activity throughout 2022-2023 is more than 2,300 Work Orders, 1000 of which are minor repairs that do not interrupt the operations, whereas the remaining are critical works with part replacements. These critical CM activities are divided based on the frequency of occurrence into eight categories as shown in Table 1. It appears roller damage is 31% of total critical works, and requires roller replacement. Accordingly, energy savings potential in terms of rollers as one of the most important parts of the BC system is suggested.

Roller Age-Related Energy Consumption

Determining roller age that has been used is not as simple visually, but perceivable from the operational temperature. Figure 4 shows the observation data obtained by thermal imager on roller bearings operating more than 2 hours, grouped by roller age. Based on the four conditions, the historical data on a BC sample was taken at four distinct periods, to identify the effect of different bearing age compositions on actual energy consumption.

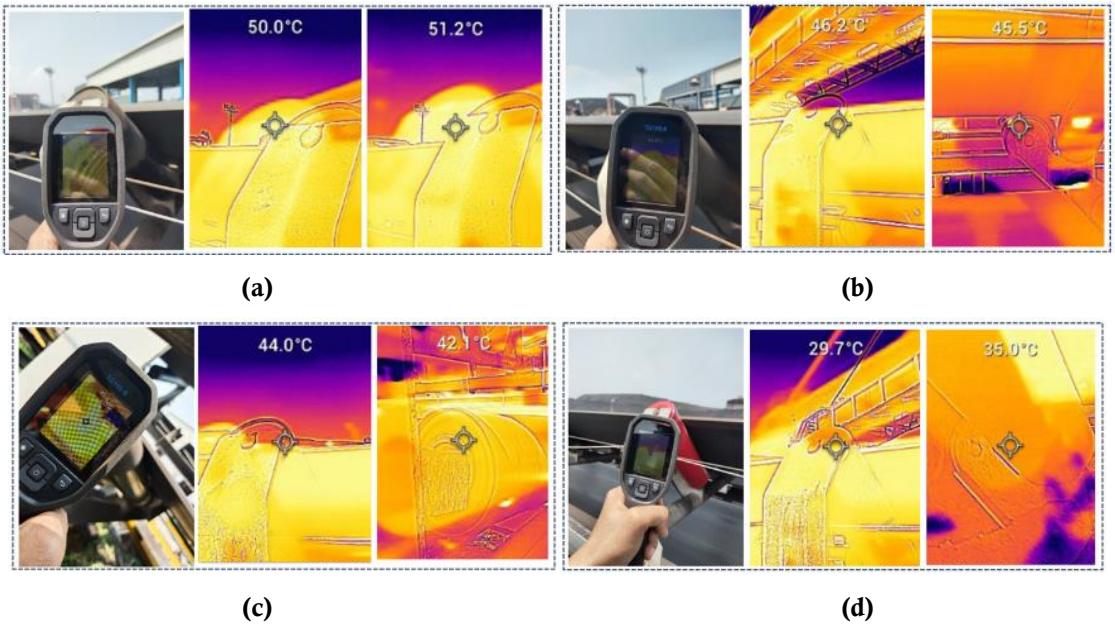


Figure 4. Measurement of bearing temperature based on Roller Age
(a) >2 years, ±50°C; (b) 15-18 months, ±45°C; (c) 6-12 months, ±40°C; (d) 1-2 months, ±30°C

Table 2. Energy Consumption of Four Conditions (in a reverse timeline)

Condition	Roller Age	Data Retrieval	Duration	Energy Cons. (kWH)
Condition 1: Presently (30% Roller Replacement)	30%: new 70%: > 2 years	6-Nov-23	2 hours	400.83
Condition 2: 18 Month from Commissioning (10% Replacement)	10%: new 90%: 18 months	10-Apr-23	2 hours	447.75
Condition 3: 8 Month from Commissioning (<1% Replacement)	1%: new 99%: 8 months	4-Jul-22	2 hours	430.81
Condition 4: First Commissioning (No Replacement)	Assumed New	6-Dec-21	2 hours	374.58

At equivalent tonnage, table 2 shows the observation results at the beginning of commissioning (condition 4), where all the rollers are assumed new, and energy consumption is

the lowest around 380 kWH in two operation hours. With the passage of time, most rollers aged and energy consumption tends to increase (conditions 3 and 2). However, in condition 1, where 30% of new rollers are installed, energy consumption drops 10% from the preceding. It indicates that new rollers with new bearings can potentially rotate more smoothly and stably, thus greatly potential to reduce energy consumption. It complies with previous research: the longer bearing operated generates the same wear pattern characteristic (Machado et al., 2019).

Verification of Calculation Data and Actual Data

This data verification should be undertaken to measure how precise the calculations are, compared to the actual data. Based on the available observation data, the approach to calculate energy consumption in BC is considering the following provisions:

1. Only takes into account the energy consumption of:
- carrier roller (based on F radial from coal)
- pulley (based on F radial from belt tension)
- motor operation for a certain load
2. Do not calculate losses of skirt and return roller friction (F radial 0).
3. Calculations were only carried out on four (from total 20) BC systems: 508A, 512A, 515A, 516A with any differences in structure and parts.
4. Calculations are carried out for load 1,500 tph, using equation (1) to (9).
5. Calculations are carried out in less than 1 hour, assuming the temperature less than 40°C.
6. Bearing energy consumption calculations were carried out using **Integrated SKF calculation MESYS** at an outer bearing temperature 40°C.

Table 3. The comparison results of Calculation and Actual Data on Energy Consumption

Data	CVY-508A W1600	CVY-512A W2200	CVY-515A W1600	CVY-516A W1600
Roller Total	3,165	6,060	1,836	1,251
Roller - Energy Cons. Total (kWH)	2.09	4.00	1.21	0.83
Total Pulley (unidentical)	7	17	13	7
Pulley - Energy Cons. Total (kWh)	37.14	199.7	92.08	36.348
Motor's Energy on 1500 tph (kW)	21.40	40.51	32.96	14.48
Energy/hour (kWh) - Calculation	**60.63**	**244.20**	**126.26**	**51.65**
Energy/hour (kWh) - Actual	**59.61**	**231.22**	**129.84**	**53.97**
Deviation (%)	**1.72**	**5.62**	**2.76**	**4.30**

Table 3 shows that BC design affects the deviation value, the more complex a conveyor system, the greater deviation is. This deviation is also possibly caused by the following matters:

1. Skirt - cleaner friction, and other types of rollers are not included in calculation, while actual friction of some conveyor parts could be an additional burden (Holmberg et al., 2017).
2. The calculation in SKF used only constant temperature at 40°C, whereas the actual temperature may vary due to bearing age.
3. Tension pulley as radial force in SKF calculation is a fixed value depending on type and size, while the actual pulley tension may be altered by the maintenance team for some conditions.
4. Tonnage as an input value in MESYS, is also a fixed value at 1,500 tph, whereas the actual tonnage may fluctuate around it.

Potential Benefits of Roller Replacement

Based on roller bearing temperature measurement in Figure 4, bearing operational temperature of ±50°C represents the age over 2 years old, while bearing operational temperature of ±30°C represents the new one. By applying Integrated SKF calculation, the energy consumption for operating an old bearing is 70% greater than new one. The existing working procedure states that roller replacement is set into 'breakdown maintenance', which means that maintenance team awaits until roller gets stuck/broken then replacing instead, reflects an increase in energy as the bearing ages because friction leads to the heavier bearing performance.

Since only roller replacement work is carried out regularly, based on the research, a simple scenario of direct replacement of only 30% of carrier rollers aged over two years from all BC systems in CHS, with the assumption that 75% of rollers are in contact to belt, could save **103,144.20 kWH** every one operational cycle. The investment of 38,400 manhours – IDR 544,051,200 for 100-day-works, and a total of 16,780 roller replacement – IDR 16,611,804,000, would result in payback for **12 weeks** only for two effective operational cycles a day.

Potential Benefits of Implementing Lean Six Sigma

Lean Six Sigma improves energy performance at CHS by implementing five DMAIC steps as explained in the introduction.

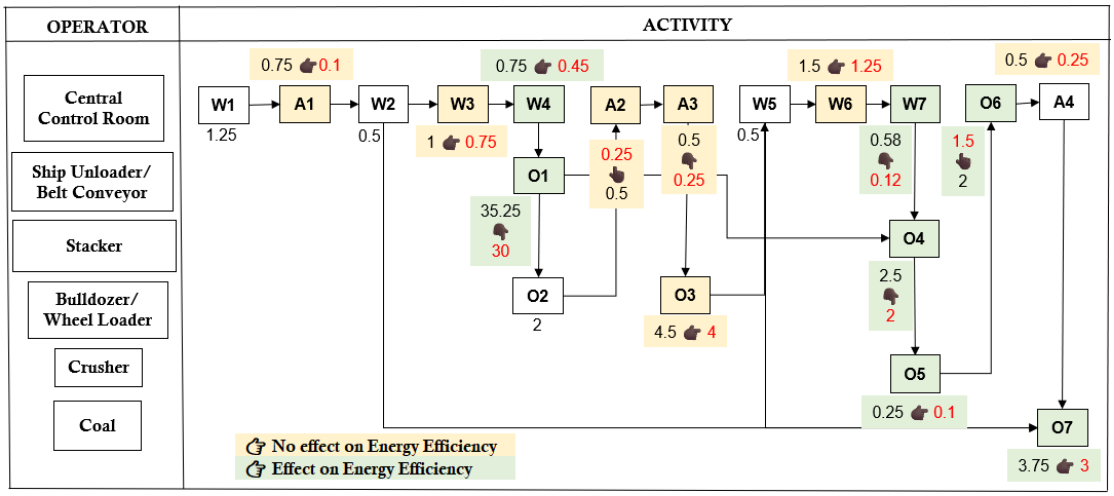


Figure 5. Current and Future State Map of Lean Six Sigma Application

The first Define-step output in CHS one operational cycle are:

W1 Waiting for vessel berthing process at jetty

A1 Inspection of administrative documents, safety checks, and toolbox meeting

W2 Waiting for CCR (central control room) instructions to start coal unloading

W3 Waiting for preparation of unloading line and cleaning the remaining coal

W4 Waiting for the unloading conveyor starting process in sequence (cleaning belt)

O1 Coal unloading process from CSU to coal yard

O2 Coal cleaning in vessels using wheel loader

A2 Re-measure tonnage of coal transferred from vessel to coal yard from belt scale data

A3 Create a report that the unloading process is complete

O3 Coal arrangement using bulldozers and wheel loaders at coal yard

W5 Waiting for CCR instructions to start coal forwarding

W6 Waiting for forwarding route preparation, cleaning of remaining coal and water

W7 Waiting for the forwarding conveyor starting process in sequence (cleaning belt)

O4 Moving coal from the coal yard to the conveyor using SR

O5 The process of refining coal in a crusher

O6 Forwarding process to Bunker/Silo

A4 Making a report on the coal forwarding process is complete

O7 CRO (coal runoff) process

Figure 5 shows steps 2 to 4 of LSS (Measure, Analyze, Improve). The average duration of each CHS activity is compared to ideal data from the technical management meeting (TMM). Then, based on work type, the current activity duration is determined which is potentially more effective, highlighted yellow. Subsequently, those that have a direct effect on energy consumption are designated in green. Therefore, the energy-saving scenarios from green highlight activities are feasible. The scenario of reducing lag duration start time among BC could obtain in savings of 931.57 kWH per one cycle, or benefits of IDR 55,712,165 per month with 20 days effective cycles. Furthermore, by considering the future state map, reducing operational time may result in energy savings of 8,984.82 kWH per cycle, similar to benefits IDR 537,332,023 every month.

CONCLUSION

Based on the analysis and research results, it can be concluded that the maintenance activities correlate with energy consumption in Coal Handling System. Roller, as the most common damaged item, has the characteristic that the older it is, the higher energy to rotate bearings inside. Direct replacement of rollers aged more than two years is highly recommended to save energy, rather than replace it when broken as mentioned in existing instruction. Simulating roller replacement of as much as 30% of total, may save 103,144.20 kWH or benefit IDR 102,807,951 in one operational cycle. Whereas applying Lean Six Sigma results saved 594,984 kWH or equivalent to IDR 593,044,189 per month.

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