Optimization operation strategy of electric boilers by mixed integer programming method in nickel production process

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Abstract. Nickel smelting process requires steam in the process of drying and calcining. Utilities Department is responsible for supplying steam either use electric boiler or fossil fuel. With fluctuations in fuel prices, limited electricity supply, boiler reliability, and government emission limits, it is a challenge for department utilities to produce steam. Planning and selection of boiler operations to produce steam to meet the needs of the smelting process are necessary in order to minimize operating costs and maintain boiler reliability in distributing steam. This condition makes mixed integer programming become the best method to solve the model. Mathematical models are used to determine boiler operations in the wet season and dry season by using mixed integer programming methods. In the wet season, boilers that use electricity can operate because electricity from hydropower is sufficient, although not fully the boiler can meet the steam needed. Whereas in the dry season boilers that use electricity cannot operate due to limited electricity supply generated from hydropower.

1. Introduction
Nickel processing in smelters requires supporting facilities to produce SWAP (Steam, Water, Air, Pressure). One of the products that become an important thing on the nickel processing plant is steam. Steam supplied to nickel processing is a product of utilities plant that consists of hydroelectric plant and thermal plant. Most of the steam used on process are produced by thermal plant. Steam are distributed to nickel process plant to fulfill fluctuate demand of steam as per shown at Figure 1.

![Figure 1. Annual steam demand quantity.](image)

Figure 1 shows that steam demand from process plant has decrease in year 2016 to 2018 due to change fuel in the kiln and dryer which initially used HSFO switched to use coal. In year 2019, steam
Demand has increased into 14.5 tons/hour due to the nickel processing plant company has the initiative to contribute green environment by reducing coal consumption. The other alternatives to support the green environment program is using electric boilers. Another consideration that makes electric boilers an option is low operating cost, but on the other side electric boiler required high power consumption. Comparison of steam generation cost and power required shown in Table 1.

Table 1. Steam generation cost comparison.

| Steam Generation Index | Unit - Fuel | 2015  | 2016  | 2017  | 2018  | 2019  |
|------------------------|------------|-------|-------|-------|-------|-------|
| PB#1a                  | Liter/Ton - HSD | 54.17 | 41.37 | 47.28 | 63.03 | 64.63 |
| PB#2                   | Barrel/Ton - HSFO | 39.06 | 24.86 | 35.51 | 41.27 | 47.27 |
| BW Boilerb             | Liter/Ton - HSD | 55.11 | 42.08 | 48.10 | 64.13 | 65.75 |
| WHRBc                  | Liter/MWh - HSD | 54.73 | 41.79 | 47.76 | 63.68 | 65.29 |
| EBd                    | MW/Ton - Hydro Electricity | 0.00  | 0.00  | 0.00  | 0.00  | 9.21  |

a PB is Package Boiler
b BW Boiler is Babcock & Wilcox Boiler
c WHRB is Waste Heat Recovery Boiler
d EB is Electric Boiler

The average steam demand for nickel processing plant is 15 tons/hour with required 10 MW of electric power if the steam supplied by electric boiler. This condition will be creating 2 MW lack of electric power condition and become the main constraint. Other constraints to be considered in this paper, to operate the electric boiler is source of water for hydroelectric generation. Hydroelectric water level is depending on the rainfall, during the dry season from October to December can barely operate because of the reduced ability of hydropower plants to generate electricity. It is caused by the height of the lake’s surface which is supplying water to hydropower plants also decrease.

Each type of boiler operated by company refer to Table 1 has each of its problem. On the other side, increasing nickel production capacity requires higher electric power, that’s why electric boiler becomes a bottleneck issue due to limited electric power sources.

![Figure 2. Towuti lake water level.](image-url)
Company fulfilled the electric power required by using hydropower plant that consist of three hydropower plants divided into 3 area, namely Larona, Balambano and Karebbe hydropower plants. These three hydropower plants water source is derived from Towuti lakes and using a cascade system for the type of water flow. The generating capacity of those three hydropower plants is highly dependent on the water level of Towuti lake that fluctuates as shown in Figure 2. Not only water level of Towuti lake, but also HSD and HSFO price that fluctuates and government emission threshold to fulfilled steam demand requirement for nickel processing become a challenge to company to do the best operation strategy that can optimize the operating cost which will be discussed in this study.

The ultimate goal of this paper is to get the optimum boiler operating cost that considers fixed and variable costs. Fixed cost will generate when the boiler operated, that’s why fixed cost decision variables will be defined by integer number 1 or 0. On the other side, variable cost define by the steam produced by the boiler, so the number of variable costs allowed not an integer number. According to those case problems, modelling by MIP approach become the best suitable method to solve the problems.

2. Mixed Integer Programming (MILP)

Integer programming is a linear programming in which some or all the variables are required to be non-negative integers. There are two categories for integer programming, the first one is called pure integer programming problem in which all variables are required to be integers, and the second is called mixed integer programming in which only some the variables required to be integers [1]. Linear Programming (LP) models remain much more attractive from a computational point of view for several reasons. When an LP problem is formulated, the software finds an optimal solution. When the formulation requires variables that are naturally integer or binary, the problem becomes a MILP model [2]. The maximum size of instances of MILP models for portfolio optimization that can be solved to optimality strongly depends on the specific model. In MILP models, an increasing number of assets makes the model harder to solve then an increasing number of scenarios, in general, it is the number of binary or integer variables that determine the computational time required. Most models with fixed transaction costs may be solved to optimality within a reasonable amount of time (on the order of hours) on instances with up to several hundreds of variables [2].

The MILP model has been developed from Method for analysis of industrial energy systems (MIND) that has been developed to solve the optimization problem for the iron and steel industry. The model is implemented in LINGO software. LINGO is a software for solving optimization problems developed by Lindo System, Inc., USA. It is a comprehensive tool designed to make building and solving linear, nonlinear and integer optimization models faster, easier and more efficient [3].

The model in this study is similar to the previous study, the difference from the previous study located on the operating strategy to be implemented [4]. On the previous study, the simulation model is modelling the blackout strategy due to large scale cascading blackout in a power transmission network, in this study will be calculated for strategy operation to get optimum operating cost. The optimal solution by building a model. There are two categories, quantitative and qualitative model. Quantitative model includes linear programming, MILP, MINLP, dynamic programming, and multi-objective programming [5].

0/1 mixed integer linear programming, as the method develop in this document, is an extension of integer programming, due to the fact that new complicating variables (0/1) are introduced. Thus, this is a new approach and the main advantage is that allows coping with a more realistic model, taking into account other important variables [6].

3. Model Development

This study is used to examine cost analysis to determine the boiler operation strategy by developing a mixed-integer programming model using lingo software through data approaches:

1. Production demand
2. Availability of electricity
3. Reliability of the boiler
4. Environmental or emissions factors,
5. Production costs (fixed and variable costs).

In making mathematical models determine the boiler operation strategy in delivering steam to customers is divided into two conditions, namely the wet season and the dry season. In the wet season, which is for January - September or the 1st day to 273th, while the dry season from October to December or the 274th to 365th day. For the mathematical model formulation uses the following notation:

**Input**

- **Index:**
  - \( i \) : Boiler
  - \( t \) : Day

**Parameter:**

- \( FC_i \) = Fixed Cost of the \( i \)th boiler.
- \( VC_i \) = Variable Cost of the \( i \)th boiler.
- \( CP_i \) = Capacity of the \( i \)th boiler.
- \( Re_i \) = Reliability of the \( i \)th boiler.
- \( EC_i \) = Electric Consumption of the \( i \)th boiler.
- \( MP_i \) = Minimum Production of the \( i \)th boiler.

**Variables:**

- \( BB_i \) = Value 1 if the \( i \)th boiler on the \( t \)-day is operating, otherwise value 0.
- \( ST_{it} \) = The amount of steam produced from the \( i \)th boiler on the \( t \)-day
- \( AB_i \) = Value 1 if the \( i \)th boiler operates, otherwise value 0.

**Objective Function:**

Minimize \( Z = (\text{Total fixed cost x Operating boilers}) + (\text{Total variable cost x Steam production}) \)

\[
\min Z = \sum_{i=1}^{9} \sum_{t=1}^{365} FC_i BB_{it} + \sum_{i=1}^{9} \sum_{t=1}^{365} VC_i ST_{it}
\]

There is a constraint also to get an optimum operating cost by modelling the operation strategy boiler. The constraint of this condition is consisting of:

1. **Rating Capacity of each boiler**
   - PB#1 = 6 Ton/hours, PB#2 = 18 Ton/hours, BW Boiler = 22 Ton/hours, Electric Boiler = 20 Ton/hours, WHRB#1 = 1 Ton/hour, WHRB#2 = 1 Ton/hour, WHRB#3 = 1 Ton/hour, WHRB#4 = 3 Ton/hours, WHRB#5 = 2 Ton/hours. Capacity is calculated daily by multiplying capacity by hours in one day (24 hours). The total steam produced by each plant every day must not exceed its capacity.
   
   \[
   ST_{it} \leq CP_i \ \forall \ i, t
   \]

2. **Steam that supply from the various boiler operated should be fulfill steam demand requirement**
   - which is 15 ton/hour. Total demand of steam for 1 day is 15 ton/hour x 24 hours = 360 Ton. Formulation of constraint that describe the steam demand is:
   
   \[
   \sum_{i=1}^{9} ST_{it} \geq 360 \ \forall t
   \]

3. **Electricity power can be provided to produce a steam is only 9 MW** and put as an RHS value in equation number (3). Mathemetic formula that describe this constraint is

\[
\sum_{i=1}^{9} EC_i + ST_{it} \leq 9 \times 24 \ \ t = 1, 2, ..., 273
\]
4. Total electricity required to produce steam is less than 1MW that refer to formula as below:
\[ \sum_{i=1}^{9} EC_i + ST_{it} \leq 1 \times 24 \quad t = 274,275,\ldots,365 \quad (5) \]

5. Physical availability of steam supply system when boiler operate during Wet Season the customer gives time for the total boiler shutdown maintenance for 2 days per-year or the Physical Availability target of the steam production system is 92.0%, combination configuration describe in mathematic formula as below:
\[ \sum_{i=1}^{273} \sum_{t=1}^{9} ST_{it} \geq 0.992 \times 360 \quad (6) \]

6. Physical availability of steam supply system when boiler operate in combination configuration on dry season describe in mathematic formula as below:
\[ \sum_{i=274}^{365} \sum_{t=1}^{9} ST_{it} \geq 1 \times 360 \quad (7) \]

7. Reliability PB # 1, PB # 2, BW Boiler, and EB are expected to be 100% or 365 days in one year
\[ \sum_{i=1}^{365} ST_{it} \leq Re_i \times 365 \times 360 \quad i = 1,2,\ldots,4 \quad (8) \]

8. Reliability WHRB#1 - 5 are expected to be 100% or 365 days in one year
\[ \sum_{i=5}^{365} ST_{it} \leq Re_i \times 4 \times 360 \quad i = 5,6,\ldots,9 \quad (9) \]

9. Minimum quantity of steam produce from PB#1 is 0.6 ton/hour, PB#2 is 1.8 ton/hour, and BW Boiler is 2.2 ton/hour, and electric boiler is 2 ton/hour. The value of minimum steam produce from each type of boiler is 10% of their rating capacity.
\[ ST_{it} \leq M \times BB_{it} \quad \forall t,i \quad (10) \]
\[ MP_{t,i} - ST_{it} \leq M \times (1 - BB_{it}) \quad \forall t,i \quad (11) \]

10. If EB is the main generator, PB # 2 is the second boiler
\[ BB_{2t} \geq BB_{4t} \quad \forall t \quad (12) \]

11. In the wet season the availability of electricity from hydropower plants can be sufficient from the demand of electric boilers, so that in the wet season the use of electric boilers is optimized. Whereas in the dry season there is no electricity available for electric boilers and during the dry season the PLTD is operated to increase the availability of electricity but the PLTD is only allowed to operate 1000 hours per year because the NOX emissions of the PLTD exceeds the government threshold. Because WHRB utilizes the exhaust gas heat from the PLTD, at that time WHRB could operate for 1000 hours or 41 days
\[ \sum_{i=5}^{9} ST_{it} \leq 0 \quad t = 1,2,\ldots,273 \quad (13) \]
\[ \sum_{i=5}^{9} ST_{it} \leq 0 \quad t = 314,315,\ldots,365 \quad (14) \]
12. If a boiler operates at a time, a fixed cost will arise

$$\sum_{t=1}^{365} BB_{it} \leq M * AB_{it} \quad \forall i$$

(15)

Expected output from the mathematic model of mixed linear programming in this study is the
decision variable that describes a steam quantity produce and the decision to operate the boiler either
should be operate or not. The resulting decision variable will be used in the calculation of total operating
cost which is the total of the component cost of the fixed cost and variable cost. Annual total operating
cost will be the sum of total operating cost on wet season and dry season. Annual total actual operating
cost from model will be compare with the annual existing total operating cost.

4. Result

The results of this analysis can be divided into two mathematical models, namely boiler operation during
the wet season for 9 months (January - September) and during the dry season for 3 months (October -
December). During the wet season, electricity from hydropower plants can meet the electricity needs for
the smelting process of nickel and electric boilers to obtain the cost of producing steam by maximizing
the use of electric boilers. Table 2 shows the results of calculations from the mathematical model.

| No | Variable | Boiler       | Steam production |
|----|----------|--------------|------------------|
| 1  | $X_1$    | Packed Boiler#1 | -                |
| 2  | $X_2$    | Packed Boiler#2 | 43.2             |
| 3  | $X_3$    | BW Boiler     | -                |
| 4  | $X_4$    | Electric Boiler | 316              |

Table 2. Steam production in wet season.

Based on the calculation of steam production from a mathematical model in 9 months, the most
optimal for the scenario of boiler operation is by operating an electric boiler and producing steam of 316
ton per-day using 8 MW of electricity. Because the demand from customers is 360 ton per-day of steam for
9 months, based on the results of calculations using lingo the shortage of steam production is met by
packed boiler# 2 with a total production of 43.2 ton per-day. With a production scenario like the results of
the above calculation, it will be known the cost of producing pressurized steam of $ 1,689,012 in the wet
season.

In September to December, the availability of electricity for electric boilers was not available, so that
during the season steam can only be supplied from boilers with fossil fuels. Table 3 shows the results of
calculations from the mathematical model.

Based on the calculation of pressurized steam production from a mathematical model, in the most
optimal 3 months is to maximize the operation of WHRB for 1000 hours and produce steam of 216 ton
per-day. Because the demand from customers is 360 ton per-day and the shortage of steam production
when WHRB operates is met by packed boiler#2 with a total production of 144 ton per-day tons.
Because WHRB cannot operate for more than 1000 hours, packed boiler#2 becomes the main boiler and
produces 360 ton per-day. With a production scenario like the result of the calculation above, it will be
known that the production cost of pressurized steam is $ 1,615,073 in the dry season.

Three months boiler operating cost in dry season almost same with nine months boiler operating cost in
wet season. It caused by in dry season electric boiler cannot operate due to lack of power generated by
hydropower plant. Fossil fuel boiler will run in dry season to provide additional power and require more
boiler operating cost. Three months boiler operating cost in dry season almost same with nine
months boiler operating cost in wet season. It caused by in dry season electric boiler cannot operate due to lack of power generated by hydropower plant. Fossil fuel boiler will run in dry season to provide additional power and require more boiler operating cost.

Table 3. Steam production in dry season.

| No | Variable | Boiler             | Steam production (Ton) | Remarks                     |
|----|----------|--------------------|------------------------|-----------------------------|
| 1  | X₁       | Packed Boiler#1    | 144                    | - When backing up           |
|    |          |                    |                        | WHRB 41 days                |
| 2  | X₂       | Packed Boiler#2    | 360                    | - After WHRB does not       |
|    |          |                    |                        | Operate                     |
| 3  | X₃       | BW Boiler          | -                      |                             |
| 4  | X₄       | Electric Boiler    | -                      |                             |
| 5  | X₅       | WHRB#1             | 24                     |                             |
| 6  | X₆       | WHRB#2             | 24                     |                             |
| 7  | X₇       | WHRB#3             | 24                     |                             |
| 8  | X₈       | WHRB#4             | 72                     |                             |
| 9  | X₉       | WHRB#5             | 72                     |                             |

After getting the value of the decision variable and entering that value into the objective function equation of minimizing boiler operating costs using mixed-integer programming, a cost-minimization analysis is performed by comparing the results of optimization with actual costs. In comparing the operating costs of this boiler with the sum of costs in two conditions, namely the wet or dry season or the operating costs of the boiler in 1 year. Operating costs obtained from the mathematical model using the mixed integer programming method during the wet season are $1,689,012 and boiler operating costs during the dry season are $1,615,073 so the total minimum annual boiler operating costs are $3,304,085. If we compare with the actual boiler operating costs 2019 with the results of mathematical model calculations using a mathematical model that calculations with mathematical models, variance only is 3.4% and can be show in Figure 3. During this time the difference between the budget and the actual is greater than 10% refer cost report 2017 – 2019.

Figure 3. Variance optimization model result with actual operation cost.
5. Conclusion

This optimization study of boiler strategy operations was conducted to obtain optimal boiler operating costs. There are several conclusions based on the results obtained from modelling. The first where the operating costs of the mathematical model is the sum of the operating costs in the rainy and dry seasons which is $3,304,085.

The second is achieving optimal boiler operating results with a mathematical model approaching 3.4% of actual boiler operations. When compared with the determination of the budget from 2017 to 2019, the budget difference from 2017 to 2019 has a very significant difference when compared to the actual production costs of boiler operations, which is above 10%.

6. References

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