Regression analysis in predicting coating application lifetime on asset integrity project

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Abstract. The Asset Integrity project is one of the strategic priorities in maintenance to ensure the functional lifetime of an asset is well maintained to support the nickel processing. The coating protection application is one of the asset integrity strategy to maintain the structural lifetime, however the corrosive environment of nickel processing plant influences the lifetime of the coating design differently on each facility due to different process in the processing line. The objective of this study is to predict the coating design lifetime on Dryer, KILN, Furnace, and Converter facilities. The analysis used regression method for coating lifetime on each facility by considering the independent variables, i.e. SO₂ Intensity, stack emission, NOx emission, rainfall intensity, and underfilm condition. By using regression model, coating design lifetime in Dryer area is 4.95 years, KILN is 5.73 years, Furnace is 6.23 years, and Converter is 6.73 years. Process plant area which having the most significant impact of corrosive environment is Dryer area, causing the coating lifetime in this area is the lowest than other area in the Process Plant area. This result can be used to set maintenance strategy for coating design lifetime lifecycle for the next Asset Integrity project.

1. Introduction

The nickel processing plant has already stood for 50 years, causing a high risk in structural failure since it already reaches the design lifetime limit, any structural failure will cause a huge impact to the operational line. There are 365 assets in the processing plant and to maintain these assets will require proper planning and strategies to set the priority on high risk asset and to execute it. Asset Integrity project is part of the Asset Management Framework (AMF) to focus on planning, and asset controlling based on technical assessment which has been done in the feasibility study. With 7% asset classified as high risk level, 19% classified as medium high risk, and 29% as medium risk, proper planning is required to manage all facilities can be maintained to ensure the production lines is not interrupted. The coating process is part of the action plan to ensure the structure design meets with design lifetime. However, the range of coating durability influenced by many factors. There are a variety of environmental stresses that combine to degrade coatings exposed in a service environment. By identifying these factors and how it correlated with the coating durability will give sufficient information to the maintenance team to predict the coating design lifetime. For this reason, multiple correlation and multiple regression are mathematical tools which allow to identify the linear simple correlation between the variables as well as the multiple correlation coefficients which may reflect the influence of one or the combined influence of two factors on the 3rd one [1].

The regression model can be applied to understand the relation between coating lifetime with SO₂ intensity, rainfall intensity, NOx emission, undercoating condition and stack emission as part of the
industrial atmosphere in the nickel processing plant focusing on Dryer, KILN, Furnace, and Converter area since this is the main operational line for the nickel processing plant. This research goal is to create a prediction model of coating design lifetime on each facility on the nickel processing plant using attributes of multiple independent variables.

2. Materials and Method

2.1. Corrosion and coating

Corrosion is generally taken to be the wastage of a metal by the action of corrosive agents. However, a wider definition is the degradation of a material through contact with its environment. Thus, corrosion can include non-metallic materials such as concrete and plastics and mechanisms such as cracking in addition to wastage (i.e. loss of material) [2]. Mechanical properties of the materials decrease by corrosion process whereas the corrosion products are released in different forms that may cause a more extreme corrosive environment or harmful side effects in different applications [7]. To overcome this issue and to enhance material properties for specific applications, there have been different methods offered, such as heat treatment, alloying processes, and coatings. Among these solutions, coating processes have the highest portion of material enhancement since coating layers can reduce the cost and neglect scarcity of materials as the thickness of coating layers rarely pass micrometres [7].

Acids consist of inorganic mineral acids such as hydrochloric, sulfuric, and nitric acids, which disassociate completely in water. Acid gases such as sulphur dioxide (SO2), sulphur trioxide (SO3), hydrogen sulphide (H2S), and nitrogen oxide (NOX) react with moisture in the air in the form of precipitation or condensation to form sulfuric and nitric acids [8][9].

Based on table 1 Nickel processing plant environment categories as C5-I for the corrosion category and this environment influence the coating design lifetime very aggressively [10]. Some of the parameters which influence the corrosion based on the feasibility study in the Asset Integrity project are SO2 intensity, surface preparation, rainfall intensity, and Process Plant environment.

Table 1. ISO 12944 (1998) - Atmosphere corrosivity categories and examples of typical environments.

| Corrosivity Category | Exterior Environment | Interior Environment |
|----------------------|----------------------|----------------------|
| C1 Very low          | ---                  | Heated buildings with clean atmospheres, e.g., office, shop, schools, hotels |
| C2 Low               | Atmospheres with low level pollution, mostly rural area | Unheated building when condensation may occur e.g., depots, sports hall |
| C3 Medium            | Urban and industrial atmospheres, moderate sulphur dioxide pollution, coastal area with low salinity | Production rooms with high humidity and some air pollution, e.g., food processing plants, laundries, breweries, dairies |
| C4 High              | Industrial area and coastal area with moderate salinity | Chemical plants, swimming pools, coastal ship-, and boatyards |
| C5-I Very High (Industrial) | Industrial area with high humidity and aggressive atmosphere | Building area with almost permanent condensation and with high pollution |

2.2. Data mining

Data mining is the process of discovering interesting patterns from massive amounts of data. As a knowledge discovery process, the process typically involves data cleaning, data integration, data selection, data transformation, pattern discovery, pattern evaluation, and knowledge presentation. The major dimensions of data mining are data, knowledge, technologies, and applications [3]. In general data mining can be classified in to two categories:

- Descriptive Mining: To characterize property of data inside the target data.
- Predictive Mining: To conduct data interference to create prediction, predictive mining involve variables or field in set of data to predict unknown value or future value from another variable [3].
2.3. ANOVA
ANOVA evaluate the effect of two or more factors as well as the interaction between them. This technique compares the average of one response variable (quantitative) between different groups (different level of one or more factors), informing whether the difference between the sample averages of the experiment is significant to state that, on repeating the experiment, the effects would continue to be verified. For each factor, ANOVA evaluates whether the variability between groups formed by their different level is significantly greater than the variability within them [4]. This is confirmed by the p-value, when the result is lower than or equal to 5% indicating the variable have significant effect to the dependent variable.

2.4. Regression
The linear regression analysis technique is applied in situations which assumes a cause–effect relationship between two or more quantitative variables and which aims to express mathematically this relationship. It is used when there is a data set with two averages for each element and the problem is to find an equation which is able to relate the two averages [4]. Regression analysis provides an objective and systematic way to analyse data. As a result, decisions based on regression are less likely to be subject to bias, they are consistent, the basis for the decisions can be fully explained and they are generally useful [5]. The modelling will be using method as follows:

1. Linear regression with multiple variables
   The regression model with more than one independent variable to explain the relation with dependent variable, the formula for regression with multiple variables as follows [6]:
   \[ Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + e \]  

2. Coefficient of determination
   The method is using statistic approach to measure the “goodness of fit” of the data in linear regression which represent is proportion or percentage of total variance for dependent variables explained by the independent variables. R-square value range from 0-1, closer to 1 means the observed variation can be clearly explained by the model inputs. in opposite; closer to 0 means the observed variation cannot be explained by the model inputs [6]. The formula for coefficient of determination as follows [6]:
   \[ R = \sqrt{\frac{\alpha_1 \sum X_1 Y + \alpha_2 \sum X_2 Y + \cdots + \alpha_i \sum X_i Y}{\sum Y^2}} \]  

3. Significance test
   Significance test or F-Test is a test for regression model to measure the linear relation of independent variables with dependent variable by comparing the F-value with F-table with \( \alpha = 5\% \). Formula for F-value as follows [6]:
   \[ F_{value} = \frac{\frac{R^2(N-k-1)}{k(1-|R|^2)}}{k} \]  

4. T-test
   The t-test is a test to analyse the contribution of independent variables related to dependent variables partially [6]. The t-test takes a sample from each of the two sets and establishes the problem statement of null hypothesis and alternative hypothesis. t-test result will be compared with p-value to identify whether the result is lower than or equal to 0.05 to understand the significance between dependent and independent variables. In t-test the null hypothesis and alternative hypothesis formulate as follows [6]:
   1. \( H_0 \): In partial; there is no significant influence between dependent variable and independent variables
   2. \( H_1 \): In partial; there is significant influence between dependent variable and independent variables

3. Result and Discussion
3.1. Data pre-processing
To evaluate the coating lifetime in processing plant area, data collection was collected from three departments and was used to create regression model. Each of independent variable data was collected from 2011 to 2019. However, it is necessary to ensure the data did not have missing values and noise. To this aim, pre-processing data is conducted to cleanse the collected data, data input for each variable was collected from Dryer, KILN, Furnace, and Converter area. Some of the value in the data was found not recorded in the 2011, therefore the variables will not be considered into the independent variables. Since considering the nickel processing plant layout, the independent variables for each area will be varies therefore some of the variables will not be considered into the modelling.

3.2. CZSQ Result
The data were processed to create regression with multiple variables modelling. The modelling was created by using five independent variables which are SO2 intensity, rainfall intensity, stack emission, NOx emission, and under film condition on four main areas Dryer, KILN, Furnace, and Converter. The variables for each area as follow:
- Dryer: Underfilm condition, SO2 Intensity, Stack Emission
- KILN: Underfilm condition, SO2 Intensity, Stack Emission, and Rainfall Intensity
- Furnace: Underfilm condition, SO2 Intensity, Rainfall Intensity, and NOx emission
- Converter: Underfilm Condition, SO2 Intensity, Stack Emission, and NOx emission

The regression model using software will produce information, i.e. coefficient determination, standard errors, F-value, and a p-value of t-test and regression equation with result as follows:

3.2.1. Coefficient determination result
The observation was conducted on Dryer, KILN, Furnace and Converter area with 50 samples on each area. The result for Coefficient of Determination as shown in Table 2.

| Location | Regression Statistic |
|----------|---------------------|
|          | Multiple R | R² | Adjusted R² | Standard Error | Observation |
| Dryer    | 0.9887     | 0.9775 | 0.9761 | 0.228 | 50 |
| KILN     | 0.9586     | 0.9189 | 0.9117 | 0.382 | 50 |
| Furnace  | 0.9115     | 0.8309 | 0.8158 | 0.525 | 50 |
| Converter| 0.9784     | 0.9572 | 0.9534 | 0.282 | 50 |

3.2.2. Significance test
In conducting F-test, the null hypothesis and alternative hypothesis as follows:
1. \( H_0 \) : there is no significant influence for all independent variables to the coating lifetime
2. \( H_1 \) : there is significant influence for all independent variables to the coating lifetime

The F-test will use the assumption to identify whether there is correlation between dependent and independent variables by comparing the p-value with \( \alpha = 0.05 \) with condition as follows:
1. If p-value is < 0.05 then \( H_0 \) is rejected and \( H_1 \) is accepted
2. If p-value is > 0.05 then \( H_0 \) is accepted and \( H_1 \) is rejected
Table 3. Significance test result.

| Location | F | DoF | F-critical Value | F-significance | P-Value |
|----------|---|-----|-----------------|----------------|---------|
| Dryer    | 668.907 | 46 | 2.806 | 6.243 x 10^{-38} | 0.05 |
| KILN     | 127.492 | 45 | 2.578 | 6.126 x 10^{-24} | 0.05 |
| Furnace  | 55.282 | 45 | 2.578 | 8.454 x 10^{-17} | 0.05 |
| Converter| 252.038 | 45 | 2.578 | 3.500 x 10^{-30} | 0.05 |

3.2.3. T-test

T-test will be conducted on this case to identify whether each of the independent variables have a significant impact to the coating lifetime. The null hypothesis and alternative hypothesis as follow:
1. \( H_0 \): There is no significant impact from each of independent variables to coating lifetime
2. \( H_1 \): There is significant impact from each of independent variables to coating lifetime

Table 4. T-test result.

| Location | \( \beta_1 \) | \( \beta_2 \) | \( \beta_3 \) | \( \beta_4 \) | \( \beta_5 \) |
|----------|---------------|---------------|---------------|---------------|---------------|
| Dryer    | -0.431        | 0.6778        | 39.099        | 6.048 x 10^{-37} | -14.427       |
| KILN     | -0.0086       | 0.9931        | 19.750        | 8.412 x 10^{-24} | 8.768         |
| Furnace  | -0.7377       | 0.4644        | 10.274        | 2.214 x 10^{-13} | 2.4099        |
| Converter| 0.0603        | 0.9521        | 28.334        | 2.480 x 10^{-30} | 4.6116        |

Note: \( \beta_1 \) = Under film condition (%), \( \beta_2 \) = SO\(_2\) intensity (t SO\(_2\)/t Ni), \( \beta_3 \) = Stack emission (mg/m\(^3\)), \( \beta_4 \) = Rain intensity (mm/year), \( \beta_5 \) = NO\(_x\) emission (mg/m\(^3\))

3.2.4. Regression equation

The regression result as shown on Table 5 for all areas in process plant.

Table 5. Regression result.

| Area     | Intercept | \( \beta_1 \) | \( \beta_2 \) | \( \beta_3 \) | \( \beta_4 \) | \( \beta_5 \) |
|----------|-----------|---------------|---------------|---------------|---------------|---------------|
| Dryer    | -3.769    | -8.0 x 10^{-04} | 14.14         | -2.1 x 10^{-02} | -   | -   |
| KILN     | -3.042    | -3.8 x 10^{-05} | 11.06         | -7.6 x 10^{-03} | 3.2 x 10^{-03} | -   |
| Furnace  | -5.098    | -3.4 x 10^{-03} | 11.55         | -            | 8.7 x 10^{-03} | -1.0 x 10^{-02} |
| Converter| -4.889    | 1.2 x 10^{-04} | 12.79         | 5.8 x 10^{-03} | -            | 2.5 x 10^{-02} |

Note: \( \beta_1 \) = Under film condition (%), \( \beta_2 \) = SO\(_2\) intensity (t SO\(_2\)/t Ni), \( \beta_3 \) = Stack emission (mg/m\(^3\)), \( \beta_4 \) = Rain intensity (mm/year), \( \beta_5 \) = NO\(_x\) emission (mg/m\(^3\))

3.3. Model Analysis

Regression model analysis for coating design lifetime at process plant area involving five independent variables as follows:

3.3.1. Coefficient of determination

The regression model in Dryer area involves three independent variables with observation of 50 samples (SO\(_2\), stack emission, and underfilm condition) with coefficient of determination of 97.75% reflects the variation in the combination of SO\(_2\) intensity, stack emission, and underfilm condition around it means with standard error of 0.228. The regression model in KILN area with coefficient of
determination of 91.89%, variation explained by the relation of SO2 intensity, rain intensity, stack emission, underfilm condition, and stack emission with standard error of 0.382. The regression model in Furnace area with coefficient of determination of 83.09% indicates variance of the data explained by independent variables of underfilm condition, SO2 intensity, rain intensity, and NOx emission with standard error of 0.525. The regression model in Converter area with coefficient of determination was 95.72% indicates variance of the data explained by independent variables of underfilm condition, SO2 intensity, stack emission, and NOx emission around it means with standard error of 0.282.

3.3.2. Significance test
The significance test for regression model in Dryer area shown that Fsignificance 6.243x10^-38 < 0.05, and F value 668.907 > Critical value of 2.806 with degree of freedom of 46. The significance test for regression model in KILN area shown that Fsignificance 6.126x10^-24 < 0.05, and F value 127.492 > Critical value of 2.578 with degree of freedom of 45. The significance test for regression model in Furnace area shown that Fsignificance 8.4547 x 10^-17 < 0.05, and F value 55.282 > Critical value of 2.578 with degree of freedom of 45. The significance test for regression model in Converter area shown that Fsignificance 3.5004 x 10^-30 < 0.05, and F value 252.038 > Critical value of 2.578 with degree of freedom of 45. By this results H0 is rejected, independent variables have significance influence on the dependent variable for Dryer, KILN, Furnace and Converter area.

3.3.3. T-test
Based on result in Table 4 the analysis of t-test for p-value result as follows:

3.3.3.1 Dryer t-test
Underfilm condition result is 0.6778 > 0.05 resulting the H0 is accepted. The underfilm condition in dryer area is not significant influencing the coating lifetime. For any additional underfilm condition causing less significant influence to the coating lifetime. SO2 result is 6.0485x10^-37 < 0.05 resulting H0 is rejected. SO2 emission in dryer area is significant to influence the coating lifetime. Stack emission result is 2.2629x10^-16 < 0.05 resulting H0 is rejected. Stack emission in dryer area is significant to influence the coating lifetime.

3.3.3.2 KILN t-test
Underfilm condition result is 0.9931 > 0.05 resulting the H0 is accepted. The underfilm condition in KILN area is not significant influencing the coating lifetime. For any additional underfilm increase causing less significant influence to the coating lifetime. SO2 result is 8.4125x10^-24 < 0.05 resulting H0 is rejected. SO2 emission in KILN area is significant to influence the coating lifetime. Rain intensity is 0.1754 > 0.05 resulting H0 is rejected. Rain Intensity in KILN area is not significant influencing the coating lifetime. Stack emission result is 2.2629x10^-16 < 0.05 resulting H0 is rejected. Stack emission in KILN area is significant to influence the coating lifetime.

3.3.3.3 Furnace t-test
Underfilm condition result is 0.4644 > 0.05 resulting the H0 is accepted. The underfilm condition in Furnace area is not significant influencing the coating lifetime. For any additional underfilm increase causing less significant influence to the coating lifetime. SO2 result is 2.2140x10^-13 < 0.05 resulting H0 is rejected. SO2 emission in Furnace area is significant to influence the coating lifetime. Rain intensity is 0.0201 < 0.05 resulting H0 is rejected. Rain Intensity in Furnace area is not significant influencing the coating lifetime. NOx emission result is 0.1328 > 0.05 resulting H0 is accepted. NOx emission in Furnace area is not significant to influence the coating lifetime.

3.3.3.4 Converter t-test
Underfilm condition result is 0.4644 > 0.05 resulting the H0 is accepted. The underfilm condition in converter area is not significant influencing the coating lifetime. For any additional underfilm increase
causing less significant influence to the coating lifetime. SO2 result is $2.4804 \times 10^{-30} < 0.05$ resulting $H_0$ is rejected. SO2 emission in converter area is significant to influence the coating lifetime. Stack emission is $3.3109 \times 10^{-5} < 0.05$ resulting $H_0$ is rejected. Stack emission in converter area is not significant influencing the coating lifetime. NOx emission result is $0.00051 < 0.05$ resulting $H_0$ is rejected. NOx emission in converter area is significant to influence the coating lifetime.

3.3.4. Regression Equation

3.3.4.1 Dryer

Based on model analysis the regression showing a good model and can be used for analysis result from regression in Dryer area based on the equation as follows:

$$Y = -3.769 - 0.0008 (\beta_1) + 14.14(\beta_2) - 0.021(\beta_3)$$

(4)

The equation shown a negative relationship between dependent variable and independent variables in Dryer area. Underfilm condition coefficient ($\beta_1$) contains negative value of 0.0008 means for every additional increase of underfilm condition, the expected coating lifetime decrease by 0.0008 on average holding all other variable constant. However, for every additional increase of SO2 emission ($\beta_2$), the expected lifetime increases by 14.14 on average holding all variable constant. For every additional increase of stack emission ($\beta_3$), the expected lifetime is decreasing by 0.021 on average holding all variable constant. The estimated average value of coating lifetime was 3.769 years when all independent variables $= 0$ (assuming all $\beta_i = 0$ is within the range of observed values).

3.3.4.2 KILN

Analysis result from regression in KILN area based on the equation as follows:

$$Y = -3.042 - 0.000038 (\beta_1) + 11.06(\beta_2) - 0.0076 (\beta_3) + 0.00321 (\beta_4)$$

(5)

The regression equation also shown a negative relationship between dependent variable and independent variables in KILN area. Under film condition coefficient ($\beta_1$) contains negative value of 0.000038 means for every additional increase of underfilm condition, the expected coating lifetime decrease by 0.000038 on average holding all other variable constant. However, for every additional increase of SO2 emission ($\beta_2$), the expected lifetime increases by 11.06 on average holding all variable constant. Also, for every additional increase of SO2 emission ($\beta_3$), the expected lifetime is decreasing by 0.0076 on average holding all variable constant. Also, for every additional increase of rain intensity ($\beta_4$), the expected lifetime is increasing by 0.00321 on average holding all variable constant. The estimated average value of coating lifetime was 3.042 years when all independent variables $= 0$ (assuming all $\beta_i = 0$ is within the range of observed values).

3.3.4.3 Furnace

Analysis result from regression in KILN area based on the equation as follows

$$Y = -5.098 - 0.0034 (\beta_1) + 11.55 (\beta_2) + 0.0087 (\beta_4) - 0.010 (\beta_5)$$

(6)

The regression model in Furnace area shown a negative relationship where underfilm condition coefficient ($\beta_1$) contains negative value of 0.0034 means for every additional increase of underfilm condition, the expected coating lifetime decrease by 0.0034 on average holding all other variable constant. Also, for every additional increase of NOx ($\beta_5$), the expected lifetime is decreasing by 0.010 on average holding all variable constant. However, for every additional increase of NOx ($\beta_5$), the expected lifetime is increasing by 0.0087 on average holding all variable constant. The estimated average value of coating lifetime was 5.098 years when all independent variables $= 0$ (assuming all $\beta_i = 0$ is within the range of observed values).

3.3.4.4 Converter

Analysis result from regression in Converter area based on the equation as follows:
The regression model in Converter area also shown a negative relationship between dependent variable and independent variables. Under film condition coefficient ($\beta_1$) contains positive value of 0.0012 means for every additional increase of underfilm condition, the expected coating lifetime increase by 0.0012 on average holding all other variable constant. Also, for every additional increase of NOx emission ($\beta_5$), the expected lifetime is decreasing by 0.0255 on average holding all variable constant. However, for every additional increase of SO2 emission ($\beta_2$), the expected lifetime increases by 12.79 on average holding all variable constant. It also happens for every additional increase of stack emission ($\beta_3$), the expected lifetime is increasing by 0.0058 on average holding all variable constant. The estimated average value of coating lifetime was 4.889 years when all independent variables $= 0$ (assuming all $\beta_i = 0$ is within the range of observed values).

### 3.3.5. Testing the regression models

By using the regression equation on each area, we can predict the coating lifetime by giving numbers for each variable. Assuming we are conducting a new Asset integrity project in 2020 and the undercoating variable ($\beta_1$) will be equal to zero due to there is no undercoating condition for new installed structure. Therefore, only four variables will be used for this regression model. From Table 6, it was shown that Converter has the longest coating lifetime duration followed by Furnace, KILN, and Dryer. From this result, the corrosive environment influences the facilities coating condition, very significant in the Dryer and it’s causing the coating lifetime deteriorated faster in this area.

### Table 6. Regression equation testing.

| Area     | Intercept | $\beta_1$ | $\beta_2$ | $\beta_3$ | $\beta_4$ | $\beta_5$ |
|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Dryer    | -3.769    | -8.0x10^{-04} | 14.14    | -2.1x10^{-02} | -        | -         | 4.95     |
| KILN     | -3.042    | -3.8x10^{-05} | 11.06    | -7.6x10^{-03} | 3.2x10^{-03} | -        | 5.73     |
| Furnace  | -5.098    | -3.4x10^{-03} | 11.55    | -         | 8.7x10^{-03} | -1.0x10^{-02} | 6.23     |
| Converter| -4.889    | +1.2x10^{-04} | 12.79    | 5.8x10^{-03} | -         | 2.5x10^{-02} | 6.73     |

**Note:** $\beta_1$ = Under film condition (%), $\beta_2$ = SO2 intensity (t SO2/t Ni), $\beta_3$ = Stack emission (mg/m$^3$), $\beta_4$ = Rain intensity (mm/year), $\beta_5$ = NOx emission (mg/m$^3$)

### 4. Conclusion

In summary, the regression analysis shows in the state that SO2 intensity, Stack emission, NOx emission, rainfall intensity may have significant effect for the coating lifetime. The prediction results also can give a relevant information to the maintenance and project team to develop action plan and strategy. Regression model can still be applied to evaluate the effect on each area with additional independent variables. Determine coating specification according to the industrial environment is very crucial to define the coating lifetime. Asset integrity project life cycle can be improved after understanding the impact of the corrosive environment to the coating lifetime.

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