Optimization of green lean six sigma for sustainable manufacturing: NOx concentration design to reduce gas emissions of the chemical industry

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Abstract. NOx is the main pollutant of air pollution produced by the activities of industrial companies. Chemical industry companies strive to control the amount of NOX emission gases in order that ensures that the company's operations remain focused on the environment as a form of a sustainable business strategy. The integration of Green Lean Six Sigma (GLSS) is an effective hybrid method to optimize and improve manufacturing process activities to be able to reduce adverse impacts on the environment. The GLSS method combines a statistical approach to optimize process parameters and improve the quality of exhaust gas emissions from the boiler. Thus, the optimal setting for the combustion control system is obtained in the operation and activity of the ammonia and urea industry.

Keywords: NOx, emission, sustainable, lean, green, six-sigma

1. Introduction

In 2019, the World Health Organization (WHO) announced that the air pollution level in several countries is still very high. The report shows that 9 out of 10 people breathe air that contains high levels of pollutants. Outdoor air pollution is a leading cause of premature death and is estimated to burden the global economy at an annual cost of USD 225 billion [1]. Air pollution cannot be separated from the processes that occur in industrial companies. Especially from the combustion process by the chemical industry which causes a lot of exhaust gas emissions that have a negative impact on the environment. These exhaust emissions generally consist of CO, CO2, SO2, and NOx [2] [3].

NOx is a hazardous component that has a significant impact on human health if it exceeds the threshold [4]. Nitrous oxide is released from high-temperature combustion. The biggest danger of NOx pollutants comes from NO2, which is formed from NO reaction with oxygen. NO2 gas can absorb the light spectrum so that it can reduce human visibility. Besides, NOx can cause acid rain, human respiratory problems, corrosion of materials, the formation of smog, and crop damage [5].

NOx is an emission gas from industrial companies Ammonia and Urea [5]. The process of making ammonia and urea requires steam. This steam is produced from the combustion process in the boiler that uses a mixture of natural gas and air as the fuel [6]. This combustion produces exhaust gas called...
Flue gas. The magnitude of flue gas component depends on the mixture setting of natural gas and air [7]. To produce flue gas with NOx concentrations within the threshold allowed by the government/regulator, a simulation is needed to obtain a combination of natural gas and air that can produce the appropriate NOx [5]. Based on this background it is necessary to study the amount of NOx content in the flue gas of the boiler pressure medium for chemical industry that tends to frequently exceeds the threshold allowed by the government amounted to 55 mg / Nm$^3$.

The company’s efforts in managing this emission gas are part of the company’s responsibility to the surrounding environment. Green Manufacturing is a competitive part of the company in ensuring business sustainability in assuring all stakeholder's satisfaction. The sustainable strategies orientation, global competition, and government policies related to climate change require the industry to adopt sustainable practices. Green Lean Six Sigma (GLSS) is an environmentally friendly approach in reducing carbon emissions while remaining focused on producing products with high specifications [8].

This hybrid method functions optimally in identifying customer needs, reducing waste, and reducing variability [9]. This method contains a combination of structured Six Sigma problem solving strategies using statistical tools with an emphasis on lean operations and is environmentally oriented [10]. Lean-Six Sigma is used in finding and eliminating the causes of errors or defects in business processes by focusing on outputs that are very important to customers [11]. Green Lean Six Sigma integration is one of the main strategies in the competitive advantage of companies, both service and manufacturing companies, especially in compiling business strategies in the era of global competition [12].

The green concept integration in the lean six sigma method will improve the previous decision analysis which has not considered environmental aspects comprehensively. In a sense, this green concept is a complement to policy-making, especially in operations, production, and other manufacturing activities. Environmental considerations are very important, especially the increasing awareness of consumers, the community, and government policies so that every business operation and activity’s company always have a good impact on the surrounding environment.

2. Research Method

Research on the NOx concentration optimization in flue gas was carried out based on a quantitative approach using an experimental method in the form of green Lean Six sigma. The experimental method is validation or testing so that all tested variables must be measured by measuring instruments or tests that have been standardized. Standardization of instruments and processing of research results were processed using inferential-parametric statistical analysis.

The data in this research consist of primary data and secondary data. Primary data include interviews, observations, tests, physical measurements, and laboratory data. Meanwhile, secondary data in this study were obtained from manual vendor, manufacture design data, narrative boiler control and SOP. Through observation, all related techniques, procedures, and activities can be clearly identified and understood. The observations carried out focused on identifying man, machine, material, and method factors. In addition, observation can also make it easier to identify problems that arise and design solutions to the problems at hand.

DMAIC (Define, Measure, Analyze, Improve, Control) is the Six sigma method steps to remove defects and improve quality related to business metrics [9] [11]. Integration of Green Lean Six Sigma aims to increase efficiency in achieving operational excellence, is complementary and is a reference for companies to make continuous improvements, especially in environmental aspects [10] [12].

A. Define (D), the process by which research begins by identifying problems.
B. Measure (M) related to the collection and evaluation of historical data. This stage is conducted to determine the variability and capability degree of a process and identifying the factors which affect the process quality.
C. Analyze (A), the data obtained from the measurement results are used as material for analysis to determine the cause-effect relationship of each process. It also to identify potential sources of variability, failure, and determination of controllable and uncontrollable variables.

D. Improve (I), begins with the data collection regarding controllable and uncontrollable factors along with a level that explains the variation in the value of each factor in a process. Determination of parameters and level combinations of controllable variables is conducted using an approach based on the Taguchi Method. It purposes to determine the experiments number and the parameter combination of each experiment. In this study, the criteria for optimization of response parameters are based on smaller the better S / N ratio. Besides, the analysis of variance (ANOVA) was calculated to identify the contribution of each parameter to quality.

E. Control (C) is carried out to ensure that improvements have a good impact on the process and allow it to be applied to similar processes. At this stage, the results are compared before and after optimization

3. Results and Discussion
The research begins with evaluating the NOx content in the flue gas from the boiler. The exhaust gas concentration is measured or monitored directly from the Central Control Room, Local Control Room and Local Control Panel. Measure phase conducted to collect and evaluate information and data historical. In Figure 1, the NOx content in the exhaust gas is close to the threshold, often even exceeding the allowable threshold.

![Figure 1. NOx trend from CEMS Analyzer](image1)

In Analyze (A) stage, a cause and effect relationship analysis is obtained the NOx emissions from combustion in the exhaust gas as shown in Figure 2.

![Figure 2. Cause and effect diagram of NOx emission](image2)
Based on the fishbone diagram, the largest contributor categories of NOx emissions that exceed the allowable threshold are Fuel Gas, Combustion Air, Flue, and Gas recirculation. The corrective action that needs to be done is to determine the optimum parameter settings in the Combustion Control System. The application of the Taguchi method is used to obtain the optimum combination of parameters carried out at the Improve (I) stage. The number of experiments and level combinations for each experiment was determined based on the Taguchi orthogonal array, through data processing using Minitab 19, a design specification was obtained with notification L9 (33). L9(33) refers to the number of experiments of 9 runs with 3 factors and 3 levels for each factor.

Testing Parameter combination based on Taguchi orthogonal array is done to identify the optimum setting. Taguchi Method implementation is based on the fact that not all factors that cause variability can be controlled completely. This method serves to identify the controllable factors (control factors) that will minimize the noise factor. During the experiment, 3 factors were manipulated to force variability to emerge so as to produce a more consistent output. Figure 3 shows the optimization results at 100% boiler load.

![Figure 3. Main Effects Plot for SN Ratios (a) and Plot for Means (b) at 100% load](image)

Based on Figure 3, it is known that Fuel Gas and Combustion Air have the highest level of influence on NOx emissions in the exhaust gas boiler. The optimum value of the process parameter for NOx emission in the exhaust gas boiler is shown at the highest value of the signal-to-noise ratio in each input parameter. While the optimum value of the process parameters for NOx emissions in the flue gas boiler is shown at the lowest value of the mean. ANOVA results show the same contribution and relationship at this stage as shown in Table 1 and Table 2.

| Source         | DF | Seq SS | Adj SS | Adj MS | F    | P  |
|----------------|----|--------|--------|--------|------|----|
| Fuel Gas       | 2  | 0.0026 | 0.0026 | 0.00132| 1.70 | 0.370|
| Comb. Air      | 2  | 0.0007 | 0.0007 | 0.00034| 0.44 | 0.693|
| Flue Gas Rec.  | 2  | 12.0915| 12.0915| 6.04574| 7809.98| 0.000|
| Residual Error | 2  | 0.0015 | 0.0015 | 0.00077|      |     |
| Total          | 8  | 12.0963|        |        |      |    |

Analysis of Variance for SN ratios variant NOx emissions from flue gas boilers that Flue Gas recirculation has the highest F value, this shows that Flue Gas recirculation has a significant contribution to NOx emissions. Likewise, in the Analysis of Variance for means that Flue Gas recirculation has a significant contribution to NOx emission. At the control stage, a capability analysis calculation is performed on the characteristics before and after the optimal parameters are implemented (Figure 4).
At the control stage, production control is carried out at a certain load. This can be seen in the combustion control system parameters consisting of Fuel Gas, Combustion Air and Flue Gas Recirculation, which are set as in Table 3 which is monitoring continuously.

Table 2. Analysis of Variance for Means at 100%

| Source            | DF | Seq SS  | Adj SS  | Adj MS  | F      | P     |
|-------------------|----|---------|---------|---------|--------|-------|
| Fuel Gas          | 2  | 0.080   | 0.080   | 0.040   | 1.94   | 0.341 |
| Comb. Air         | 2  | 0.034   | 0.034   | 0.017   | 0.81   | 0.552 |
| Flue Gas Rec.     | 2  | 358.047 | 358.047 | 179.023 | 8617.75| 0.000 |
| Residual Error    | 2  | 0.042   | 0.042   | 0.021   |        |       |
| Total             | 8  | 358.202 |         |         |        |       |

Table 3. Combustion control setting

| Boiler Load       | Parameter       | Nm³/h |
|-------------------|-----------------|-------|
| 50 % Load         | Fuel Gas        | 4800  |
|                   | Combustion Air  | 50000 |
|                   | Flue Gas Recirc. | 8400  |
| 75 % Load         | Fuel Gas        | 7100  |
|                   | Combustion Air  | 80000 |
|                   | Flue Gas Recirc. | 12000 |
| 100 % Load (Optimum Setting) | Fuel Gas | 9200 |
|                   | Combustion Air  | 102000|
|                   | Flue Gas Recirc. | 16000 |

Figure 4. Comparison of Capabilities between before and after Optimal Parameters Implementation

Based on the change in process characteristics (Figure 4), it can be identified that there is a decrease in the percentage of quality characteristics out of the specification by 79% from 54.17% to 11.42%. The decrease in the percentage of out-of-spec was caused by a shift in the process to the left from the specification limit followed by a decrease in the average NOx emissions to 36,402 and a decrease in the standard deviation to 15,440.
4. Conclusions

The cause-and-effect diagram describes the potential categories that cause NOx emission passing the tolerable threshold into 4 main categories, namely measurement, machine, material, and environment. Machine factors which include Fuel Gas, Combustion Air, Flue, and Gas recirculation set points in the Combustion control logic are significant contributors to high NOx emissions in boiler exhaust gases while another factor is the noise factor. Based on the ANNOVA SN ratios validation results and the mean, it can be concluded Flue Gas recirculation have a very significant contribution to NOx emission. Fuel gas and combustion air are not entirely significant impacts on NOx emission, but these parameters have a direct impact on determining the optimum setting in the Combustion control Operation. Based on the results, companies can apply a combination of Combustion Control System parameters obtained from the research results to obtain NOx emissions in exhaust gases below the threshold allowed by the government.

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