A New Approach of Controlling Medium Consumption with Applications in Coal Mining Industry

QINGHE YUAN1*, XIANHUI YIN1, SHUN JIA1 and ZHAOJUN LI2

1Mining and Safety Engineering College, Shandong University of Science and Technology, Qianwangang Road, Qing Dao, Shandong Province
2Department of Industrial Engineering and Engineering Management, Western New England University, 1215 Wilbraham Road, Springfield, MA 01119

(Received on October 01, 2015, Revised on February 01, 2016)

Abstract: In order to reduce the medium consumption of dense-medium coal separation, trace back the root causes and key factors of high medium consumption, and provide an efficient solution, the limitation of the existing research is examined and the application of Lean Six Sigma to the medium consumption reduction is studied. By defining the waste and defection in the control of medium consumption and analyzing the inapplicability of the existing model, a lean sigma based method with detailed implementation procedures is proposed. The proposed method was implemented to reduce medium consumption of dense-medium coal separation in a coal mining industry, and the medium consumption is reduced from 2.17kg/t to 0.59kg/t. The application of the proposed method demonstrates that the new method can facilitate identifying and analyzing the root causes and key factors of medium consumption. In addition, the proposed approach and the outcomes from the case study establish a theoretical foundation for generic coal preparation applications in which medium consumptions are of major concerns in terms of cost saving and efficiency improvement.

Keywords: Medium Consumption, Lean Sigma, PIMAISC Model, Dense-medium coal separation

1. Introduction

Medium consumption is a major economic metric in the production and management of dense-medium separation and a significant part of the coal cleaning cost. The level of medium consumption directly affects the economic returns of a coal preparation plant and well reflects the technological & managerial capabilities [1]. There exist large variations in terms of the quantity of medium consumption among different coal preparation plants. The latest standard[2] of medium consumption regulated in the “Engineering Design Code for Coal Cleaning and Selection” states as follows: lump coal systems <0.8 kg/t; blended coal systems <2.0 kg/t; slack coal systems <2.0 kg/t. In reality, it is very difficult to reach the regulation standard for most Chinese coal plants and a 1.5 kg/t level indicates a well performing coal plant. In most cases, the medium consumption level in coal preparation plants is about 3 kg/t, and the medium consumption level in some coal plants is around 5~6 kg/t. The medium consumption level in few coal plants even reaches as high as 10kg/t or even higher [3]. The fact of high medium consumption in dense-medium coal preparation plants has lasted for decades and medium consumption improvements are usually approached through investment in new equipment or introducing new process for the medium consumption reduction. However, reducing the medium consumption by introducing new equipment often has very insignificant savings and can even lead to
Qinghe Yuan, Xianhui Yin, Shun Jia and Zhaojun Li

174

In conclusion, this research consists of three parts, which includes 1) analyzing the inapplicability of the existing model, 2) defining the waste and defection in the control of medium consumption and establishing a detailed control model combining both quantitative and qualitative analyses of medium consumption in coal preparation enterprise, 3) providing a complete application in a case study. The remainder of the paper is constructed as follows. Section 2 investigates the relationship between Lean Six Sigma and the coal preparation application. Limitations of the existing methods for medium consumption control are discussed in this section. This section also introduces the new method, i.e., “Preparation, Identification, Measurement, Analysis, Improvement, Standardization, Control” (PIMAISC) model, and the 18 steps for implementing this method. Section 3 demonstrates the application of the proposed method in controlling medium consumption with PIMASIC model in coal mining industry. Section 4 concludes the paper with discussion and future research work.

2. Control model of medium consumption based on Lean Six Sigma

Gijo et al. [11-14] proposed that Lean Six Sigma is a new method with integrated lean production and six sigma management, and it is applied to different industries. The management model of Lean Six Sigma is called DMAIC (Define, Measure, Analyze, Improve, Control) [15]. In this research, Lean Six Sigma is a management model with quality and speed considered, and medium consumption level is used to evaluate the quality and value. High medium consumption suggests that there are quality defections and wastes. In order to eliminate wastes and reduce defections, it is reasonable to apply the principle of Lean Six Sigma to the whole process of the consumption of medium.

Because of the differences between coal preparation industry and manufacturing industry, it is difficult for most coal preparation enterprises to implement Lean Six Sigma
The difficulties include: 1) top leaders who pay more attention to production than management cannot participate in the implementation, 2) management mostly depends on experience, the standardization is insufficient and the management models are quite different, 3) lack of training for employees and new models cannot be accepted easily, 4) the insufficiency of field data goes against quantitative analyses, 5) the improvement cannot be standardized and applied to other units. Therefore, the Lean Six Sigma based PIMAISC model is proposed (Figure 1). The participation of leaders, standardization and other content are added to the model and advanced statistics methods are minimized.

The proposed PIMAISC model consists of 7 stages: Preparation, Identification, Measurement, Analysis, Improvement, Standardization and Daily control, and the seven stages are divided into 18 steps for implementation (Figure 1). Preparation stage aims to gain the support of leaders about manpower and material resources and carry out propaganda and training of Lean Six Sigma. Identification stage aims to find the problems and defects through the analysis of the internal and external customer demands or the differences between real situation and standards, then the problems are quantified in this stage. Measurement stage consists of reliability analysis of measuring system, stability and gap analysis of defects data, technological processes and process analysis, defect analysis and significant factor’s confirmation and improvement. Analysis stage is divided into reliability analysis of significant factors and ide analysis of significant factors. Improvement stage consists of optimization of improved order, implementation of improved scheme and test of improved effect. Standardization stage is the process of making standard file. The Control stage consists of Statistical Process Control (SPC) analysis of defects and influencing factors and efficiency statistics. All of the steps under the Lean Six Sigma are used to achieve the control purpose of medium consumption.

| PIMAISC Model | Preparation | 1. Leaders Support  
|               | Identification | 2. Propaganda and Training  
|               |               | 3. Customer’s Voices  
|               | Measurement | 4. Comparison Standard  
|               |               | 5. Goal Quantity  
|               | Analysis | 6. Reliability Analysis of Measuring system  
|               |               | 7. Stability and Gap Analysis of Defects Data  
|               |               | 8. Technological Process and Process Analysis  
|               |               | 9. Defect Analysis  
|               |               | 10. Significant Factor’s Confirmation and Improvement  
|               | Improvement | 11. Reliability Analysis of Significant Factor  
|               |               | 12. Ides Analysis of Significant Factor  
|               | Standardization | 13. Optimization of Improved order  
|               |               | 14. Optimization of Improved order  
|               |               | 15. Test of Improved Effect  
|               | Control | 16. Standard File  
|               |               | 17. SPC Analysis of Defects and Influencing Factors  
|               |               | 18. Efficiency Statistics  

Figure 1: The PIMAISC Model and Key Implementation Steps
3. Case study

3.1 Preparation stage

In X coal preparation plant, the lead team was established to promote the project. The team is made up of manager, vice manager, technical supervisor and financial supervisor. And they will provide support of human resources, material resources, financial resources (step 1). Meanwhile, propaganda and training of the PIMAISC model has been considered (step 2).

3.2 Problem identification stage

In the coal preparation plant, the calculation method about medium consumption of dense-medium separation is the ratio of the monthly consumption of magnetite powder and the quantity of feed coal in slant wheel separator [16]. According to the record of the monthly medium consumption in the first nine months of 2015, the average medium consumption in dense-medium coal preparation plant was 2.17 kg/t, which was much higher than the standard in “Code for Design of Coal Cleaning Engineering”. So it shows the urgency of the control of medium consumption in dense-medium (step 3–step 5).

3.3 Measurement stage

The data of medium consumption was obtained by calculation rather than measure. Thus, it should not be used as analysis for the reality check of defect data. According to the principle of statistics, when the data volume reaches a certain number, the whole distribution shows normality. According to the normality test of the monthly medium consumption in the first nine months, the data of medium consumption shows a normal distribution. And it also indicates that the statistical data of medium consumption is real (step 6–step 7).

In order to illustrate current situation of medium consumption in dense-medium coal preparation plants, the process capability Cpk of the medium in process was analyzed with the condition that upper limit was 1.2 kg/t and lower was 0. The Cpk = -5.36, it suggests the process ability is seriously insufficient and the whole processes should be improved [17].

High medium consumption is the result while the loss of medium in the processes is the reason. Therefore, when the process capability is insufficient, the key process leading to high medium consumption should be determined and the status of the key process should be acknowledged and analyzed. The process flow of medium consumption in dense-medium coal preparation plants was shown in Figure 2 (step 8).
Figure 2: The Process Flow Diagram of Medium Consumption

As shown in the process flow diagram, the key links which influencing medium consumption were complement of fresh medium, de-medium and recovery in magnetic separation. The defect of high medium consumption was divided into high medium quantity of products and poor recovery capacity of magnetic separator after the determination of key process. Among them, medium quantity of products includes two indexes of medium quantity of gangue and lump coal. And the recovery efficiency of magnetic separator could be measured by medium quantity of tailings. Through collecting the quantity to the three indexes and calculating the ratio of quantity of total consumption, the medium quantity of gangue and lump coal were determined as major defects based on the Pareto Principle. And the reason of high medium quantity of products was analyzed by 5M1E. The description of problems and reasons should use the form of ‘noun + negative description’ [18]. 20 influencing factors were obtained through the analysis of 5M1E. In order to further screening important influence factors for medium quantity of products, narrowing the scope of control, through analyzing the 20 factors with causal matrix and combining the Pareto Principle, the key influence factors were selected from 20 factors [19]. They are the poor efficiency of de-medium, the unqualified medium density, the unqualified processes of de-medium & recovery and unqualified magnetite powder. The main factors by analysis of causal matrix cannot reach the degree of control. Therefore, controllable factors of medium consumption were analyzed by Failure Mode and Effects Analysis (FMEA) [20]. The main controllable factors are the quantity of water and the hydraulic pressure. (step 9- step 10)

3.4 Analysis stage

For reliability analysis of the measure system about quantity of water and hydraulic pressure, the method that combination of quantitative and qualitative was adopted. Reliability analysis of water meter data was more complex due to the cumulative measurement. But water meter belongs to the national legal measuring instruments, which can be analyzed by judging the completeness of metrology system in coal preparation plant. In order to gain more accurate analysis, measurement system analysis is used for pressure gauge.

Through the research, the quantity transfer was conformed to the standard of the country in the coal preparation plant, so the data of water meter is effective. The system data validity of pressure gauge was tested by concrete test. The pressure gauge of
measuring the press of spray water in a late-stage study was selected for testing. The location of the 10 different pressures was tested by 2 operators and everyone measured three times in the same place in a short span of time. Repeatability and reproducibility of this measurement system are 2.62% and 8.64% separately. Precision index % R & R is 11.26%. So the measuring system can be seen well, it can be used in the production process.

In order to illustrate the significant influence of factors for defects, regression analysis was adopted to verify the relationship between the quantities or pressure of water and the medium quantity after de-medium. Because of the reliable water meter and pressure gauge, the data of spray water de-medium can be recorded. Quantity of water pressure was set at 0.8 m³/t. The related data was as shown in Table1 (A: Quantity of water (m³/t); B: Medium quantity g/t; C: Hydraulic pressure (MPa)).

Table 1: The Experimental Date of the Influence of Water Quantity and Pressure

<table>
<thead>
<tr>
<th>No</th>
<th>A</th>
<th>B</th>
<th>No</th>
<th>A</th>
<th>B</th>
<th>No</th>
<th>C</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3</td>
<td>1212.3</td>
<td>6</td>
<td>0.8</td>
<td>156.9</td>
<td>1</td>
<td>0.10</td>
<td>1142</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
<td>950.2</td>
<td>7</td>
<td>0.9</td>
<td>131.1</td>
<td>2</td>
<td>0.12</td>
<td>943</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>680.6</td>
<td>8</td>
<td>1.1</td>
<td>117.3</td>
<td>3</td>
<td>0.14</td>
<td>706</td>
</tr>
<tr>
<td>4</td>
<td>0.6</td>
<td>410.1</td>
<td>9</td>
<td>1.2</td>
<td>110.5</td>
<td>4</td>
<td>0.16</td>
<td>513</td>
</tr>
<tr>
<td>5</td>
<td>0.7</td>
<td>226.7</td>
<td>10</td>
<td>1.3</td>
<td>100.8</td>
<td>5</td>
<td>0.18</td>
<td>302</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As shown in Figure 3(a), there was a quadratic regression relationship between the quantity of spray water and the medium quantity of product under the premise that R-Sq = 99.0%, and as shown in Figure 3(b), there was an obvious relationship between the hydraulic pressure and the medium quantity of product. Therefore, improving the spray water quantity and pressure was helpful to reduce the medium consumption (step11-step12).
3.5 Improvement stage

In analysis stage, it was verified that there was a relationship among water quantity, pressure and medium quantity of product. Through synthesizing each kind of situation, the sequence of modification of water quantity and water pressure was determined (step 13).

According to the national standard, the range of spray water quantity in dense-medium separation is 0.5-1.0 m³/t and hydraulic pressure is 0.15-0.3MPa. But the range was too large to select an adaptive rage for coal preparation plant. Thus the range should be set with the actual of coal preparation plant. As shown in Figure 3(a), the quantity of medium was tapered with the increase of spray water and hydraulic pressure before the spray water quantity at 0.8 m³/t, and the lowered range of medium consumption was large. After at 0.8 m³/t, the range of medium consumption was stable. In the similar way, 0.24MPa was the watershed of hydraulic pressure. So the suitable water quantity is 0.8 m³/t, and the suitable pressure is 0.24MPa in the coal preparation plant.

The specific improvement measure was that pressure equipment were installed to make the hydraulic pressure in the scope of 0.24±0.01MPa before the spray water entering into medium draining screen and the quantity of water was controlled in the scopes of 0.8±0.05 m³/t. In these scopes, good efficiency of spray water needs have suitable diameter of nozzle. The nozzle size was confirmed by formula (1) and formula (2) [21].

\[ Q = 3600 \frac{\mu}{4} \sqrt{200gH} \text{ m}^3/\text{h} \]  \hspace{1cm} (1)

\[ \mu = 0.32H + 0.96 \]  \hspace{1cm} (2)

Where, \( \mu \)—Flow Coefficient ; \( d \)—nozzle diameter, m ;

\( g \)—Acceleration of Gravity, m/s² ; \( H \)—Working pressure, MPa

The current throughput of medium draining screen in dense-medium separation plant was 16.4t/h. It means the quantity of spray water was 16.4t/h*0.8m³/t=13.12m³/h. One spray has four nozzles. The suitable quantity of water for each nozzle was 0.2m³/t. And the quantity of water for each nozzle was 13.12/4=3.28m³/h. The pressure was 0.24. The diameter of pipe (d) is 7.73mm. After the adjustment, the changes of improvement about medium quantity after de-medium was as shown in Table 2 (A/a: previous/improved medium quantity of coal after separation; B/b: previous/improved medium quantity of gangue after separation) (step 14). Comparing with the medium quantity of coal before and after improvement, the hypothesis of two-samples T was adopted [22]. \( p=0.00 \) was shown in the result as shown in Table3, which means the effect of improvement was obvious. It can be proved that the medium quantity of gangue is reduced obviously in the same way (step 15).

<table>
<thead>
<tr>
<th>Table 2: The Record of Changes about Medium Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date Item g/t</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>a</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>b</td>
</tr>
</tbody>
</table>
Table 3: The T-Test Analysis about Medium Quantity of Coal

<table>
<thead>
<tr>
<th>Item</th>
<th>N</th>
<th>Mean</th>
<th>St Dev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>previous</td>
<td>11</td>
<td>1241</td>
<td>113</td>
<td>34</td>
</tr>
<tr>
<td>improved</td>
<td>11</td>
<td>163.55</td>
<td>5.85</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Difference = \( \mu \) (previous) - \( \mu \) (improved)
Estimate for difference: 1077.6
95% CI for difference: (1001.4, 1153.9)

T-Test of difference = 0 (vs not =): T-Value = 31.50  P-Value = 0.000  DF = 10

3.6 Standardization stage
Standard documents should be made for coal preparation plant after improvement. Such as spray water quantity and pressure, they should be standardization in technology standard, and the guide book of standard operation should be formulated (step16).

3.7 Daily control stage
The daily control situation of medium consumption was analyzed to make SPC control chart, as shown in Figure 4.

![Xbar Control Chart for Medium Consumption](image)

**Figure 4:** The SPC Control Diagram of Medium Consumption Control

As shown in the chart, the medium consumption was in control (step17). Medium consumption of dense medium separation plant was 2.17kg/t before introducing Lean Six Sigma. After improvement, it was 0.59 kg/t. The hypothesis was that the material coal in slant wheel separation still is 269280t; the price of magnetite powder is 850 yuan per ton. So the economic returns of dense-medium separation plant are as follow (step18):

\[
\text{Economic returns} = (2.17 - 0.59) \times 269280/1000 \times 850 = 361,643 \text{ yuan}
\]
4. Conclusion

In order to improve economic efficiency, Lean Six Sigma was adopted in analysis and improvement of medium consumption, based on which, PIMAISC was proposed to establish a scientific and systematic analysis model for medium consumption reduction. Through the PIMAISC, medium consumption was dropped from 2.17kg/t to 0.59kg/t with an example of the X coal separation plant. The result shows the model can be used quantitatively and qualitatively to analyze the fundamental problems of higher medium consumption. The current approach of controlling medium consumption can be further improved from the following two aspects, 1) integrating the approach with lean thinking and tools, and 2) integrating the approach with statistical rigorous theory and methods for process improvement, which will be our future research topics.

References

Qinghe Yuan, Xianhui Yin, Shun Jia and Zhaojun Li


Qinghe Yuan is a professor and director of College of Mining and Safety Engineering at Shandong University of Science and Technology specializing in Resource Economics and Management, Industrial Engineering and system theory. He has completed over 20 research awards, published over 50 technical papers and is the author of two books.

Xianhui Yin was born in 1990 in Shandong Tai’an. He is a postgraduate student of Shandong University of Science and Technology. He specializes in Industrial Engineering and Management, Quality Management, Lean Production and Management of mineral enterprise.

Shun Jia received the Ph.D. degree in industrial engineering from Zhejiang University. He is a lecturer of Shandong University of Science and Technology where his research interests include Low Carbon Manufacturing, Green Manufacturing and Industrial Engineering.

Zhaojun Li is an Assistant Professor at the Department of Industrial Engineering and Engineering Management, Western New England University in Springfield, MA. Dr. Li’s research interests focus on Reliability, Quality, and Safety Engineering in Product Design. He earned his doctorate in Industrial Engineering from the University of Washington in 2011.