

Prediction of novel operating parameters using Six Sigma: A study in the steel making process

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ABSTRACT

It is now imperative to improve global competitiveness in an organization by upgrading process performance, enriching operational excellence besides organizational excellence. This paper illustrates flexible and practical application of Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) to optimize the process parameters for the operating regime for dephosphorization in hot metal with low silicon ($< 0.4\%$) while steel making. The statistical techniques such that hypothesis testing, non-parametric test and regression techniques were used to statistically define the key process parameters which had significant impact on dephosphorization. Six Sigma methodology was adopted to define the optimal values required to achieve the desired phosphorus level ($\leq 0.015\%$). This paper is based on case study of a renowned steel company of India, imprints that amount of oxygen blown and tapping temperature were significantly impacting the above dephosphorization process. The regression model was recommended for reference of steel engineers and managers for maintaining an optimum level of above process parameters in augmenting production of low Phosphorus steel grade. Steel industrialists, academics, consultants, researchers and Six Sigma practitioners will benefit from this study. The success of this study would help more such industries in improving the performance of similar processes.

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1. Introduction

With the advent of greater implementation of better standard practices, the emphasis is on the customer's satisfaction, which drives the focus on quality in addition to improvement in product, process, and services. The improvements in processes are simply understanding the knowledge of an existing process and then modifications in processes aimed at finding optimum values of the parameters of the process in order to enhance product quality, decrease costs or increase overall process efficiency. This technique employed for finding the optimal values of the parameters of the process is the new application of Six Sigma.

Six Sigma is a strategy for improvement of processes in several sectors such as production, financing, healthcare, etc. Linderman et al. (2003) stated that "Six Sigma is a structured and methodical strategy for planned target-oriented process improvement and creation of new products and services, based on statistical methodologies and scientific procedures, to dramatically decrease the defect rate distinguished by customers.

The DMAIC framework in Six Sigma is a five-stage cycle for process improvement, i.e., (Define, Measure, Analyze, Improve, and Control). The objective of problem-solving DMAIC is to identify the limitations of the process that induce attempts at its improvement (Braunscheidel et al. 2011). In various manufacturing sectors, techniques and tools of the Six Sigma have been executed which frame a control plan to regulate the variation to suitable levels, eliminate the variation in the processes (Revere and Black 2003) and improves the process capability (Montgomery 2010).

1.1. Six Sigma methodology

1.1.1. History of Six Sigma

Carl Friedrich Gauss gave definition of the standard curve which serves as the foundation for the Six Sigma approach (1777-1855). Since 1920, when Shewhart Walter first showed that a process has to be improved when it is three sigma off the mean, six sigma has been used as a measuring criterion for process variance. Although the majority of metric

standards (Cpk, zero defects, etc.) were revealed later, the phrase "Six Sigma" is credited to an engineer called Bill Smith who worked at Motorola. Bill Smith determined in 1983 that investigating and testing did not discover all product defects. These flaws were noticed by customers and it resulted in product failure. As the process failures were greater than Becker's, as seen in the final product test, Smith found that Six Sigma is the best approach in improving processes to decrease the problem of defects. Galvin created a long-term quality programme named "The Six Sigma Quality Program" in 1987. The program was a business initiative that developed Six Sigma. According to nomenclature of Six Sigma, the "Sigma level" of a company stands for the extent of its performance (Pyzdek 2010). The Six Sigma level equals 3.4 DPMO (defects per million opportunities) (Gijo, Scaria, and Antony 2011), that means to make a method that does not produce more than 3.4 defects per one million of manufactured products (Patel and Desai 2018).

Six Sigma is an advanced management program, which has an innovative strategic dimension that contributes to build and sustain continued success through a consistent combination viz: management and statistics, flexibility and organizational accuracy, continuous operational improvement and fulfilling the changing requirements of customers (Tennant 2017), including markets, technology, staff, stakeholders (Prashar 2014).

As stated by (Pascal and Shook 2015), defects consume more energy, materials, and time through rework. In the same way, according to (Slack, Chambers, and Johnston 2010), DMAIC helps to identify defects regarding quality including upsurge in rework, warranty, inspection, scrap costs, service along with processing time and inventory. The successful implementation of DMAIC augments the operational performance of a process. (Gaikwad and Sunnapwar 2020)

1.1.2. The PDCA cycle & Six Sigma

The PDCA cycle is innately present in Deming's method. Ishikawa (1982) somewhat modified the PDCA cycle to incorporate objectives, priorities and strategies for achieving them besides involvement of education and training (Norman 2006). For instance, Linderman et al. (2003) hypothesized that Six Sigma is based on the PDCA cycle when it comes to process improvement. According to Lucas (2002), Six Sigma employs a modified PDCA management framework. Six Sigma and TQM are built on a PDCA management framework, as per (Cheng 2008) and (Graves 2000).

The Plan stage is typically devoted to methodolo-

design, as well as management of human resources (Conti 1997). The DMAIC cycle (Define, Measure, Analyze, Improve, and Control) is useful for analyzing the process, leading a new way to think of the causes that adversely influence the studied process, recommending a structured analysis and development of series of experiments to achieve the improvement in process as well as in quality (Barbosa et al. 2017)

The Do stage is the implementation phase where the consumer's voice is captured till the goods is delivered (Conti 1997). In the Do stage, Ishikawa (1985) also included the training and skills. According to Harrington (1986), Six Sigma often reduces external Cost of Poor Quality like warranty expenses, complaints, returns and repairs.

The organization inspects to see where it complies with the Plan stage and continues to act on what it has learned during the Check and Act stages (Johnson 2002). Six Sigma seeks to provide long-term process resolution in order to improve the business processes (Snee 2010) thereby helping the organizations and industries to increase the effectiveness (Nienaber and Martins 2020) and profitability (Sordan et al. 2020). So, Six Sigma has established significant responsiveness among industrialists, scholars, and academics (Näslund 2008; George et al. 2005).

Figure 1 depicts the method of implementing strategies to accomplish the same fundamental goal i.e., process improvement.

1.1.3. The core principles of Six Sigma (DMAIC technique for process upgradation)

One of the major approaches of Six Sigma methodologies is DMAIC.

The DMAIC (Define, Measure, Analyze, Improve, and Control) principle is the most crucial element of

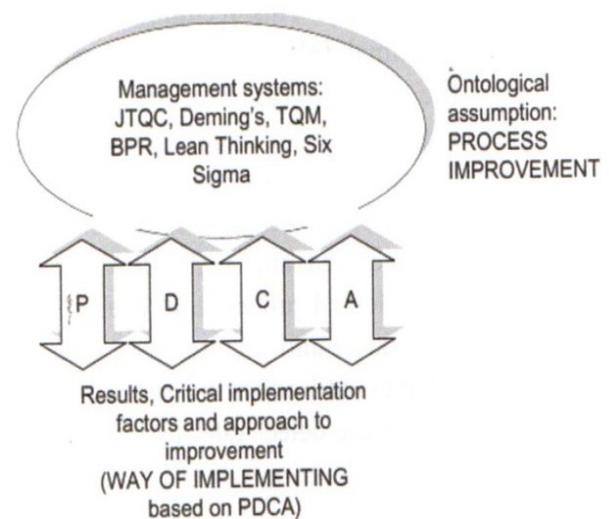


Figure 1. Ontological assumptions and system implementation

Six Sigma that is employed in the organization for process improvement.

In the pursuit of operational excellence (Rodgers et al. 2019), the DMAIC in the competitive context helps the organizations to deliver products and services through constant process improvement and continuous reduction of costs (Costa, Silva, and Pinto Ferreira 2017).

The step-by-step DMAIC technique for Process Improvement in the following five stages based on Identification, Analysis, Optimization using statistical techniques are as follows (Antony, Gijo, and Childe 2012):

Define. Ascertain the specific problem, formulate the problem statement, set and strategize the improvement initiative (Jirasukprasert et al. 2014).

Measure. Map out the current process, data-collection from the process, understand the current level of KPIs (Key Performance Indicators) and Measurement System Analysis for determining the 'Y' as well as its specific limits for continuous improvement (Tsong 2006).

Analyze. Analysis of Root-Causes is done to detect the basis for the problem of the business process, determine and validate the origin of variation, and establish the process capability (Swarnakar and Vinodh 2016).

Improve. Conduct tests and statistical methods for possible improvements, test the improvements to upgrade the process and to eliminate defects, and bad quality in products (Ziegel et al. 1999).

Control. Monitor the process through full-scale implementation of an improvement in action plan, identify the distinct variation so that remedial actions can be initiated to rectify the problem in advance, obviate the production of non-conformances. (Stamatis 2004).

2. Research background

In this era of competition, producers and consumers demand high-quality steel. However, quality grade of

raw materials (iron ore and coke) is diminishing, as raw supplies are not endless. In this changing scenario of degradation of raw material, more impurities must be handled by the steel industry, but their end products must have less impurity. The work of the authors was conducted at a renowned steel company XYZ of India. Here, the end product steel is produced through the integrated blast furnace-basic oxygen furnace (BOF) route. During this procedure, the iron ore (iron ore from mines having impurities) and coke in the blast furnace form the liquid hot metal. This liquid hot metal from the blast furnace has unwanted impurities (Sulfur, silicon, and phosphorus), those need removal. In the hot metal pretreatment in the industry, normally, most of the Sulfur is removed. Then, the desulphurized (most of the Sulfur has been removed from hot metal) hot metal along with lime, dolomite, and scrap is charged to the Basic oxygen furnace (BOF), and it is oxidized there in the presence of pure oxygen blown resulting in removal of most of the phosphorus and silicon. The produced liquid steel from BOF is tapped, that has a phosphorus content of about 0.15-0.22% and silicon content of about 0.3-0.5%. Then it is passed through various stages in secondary steelmaking to obtain the desired composition by addition of alloying elements to be cast into solid steel. Figure 2 demonstrates a diagrammatic outline of the current steelmaking process. However; the industry is still striving to make its end product steel more quality in respect of phosphorous content. A technique of tapping a steelmaking furnace involves identifying the desired level of steel to be obtained in a ladle after transferring molten steel from the furnace to the ladle. Immersion probes equipped with sensors are most typically used to monitor the temperature of molten metal.

The process that has been considered for the research paper in consultation with the company concerned, is the sub-process of steelmaking called dephosphorization. The purpose of dephosphorization is to control the phosphorus content as per the requirement of steel grades for automobile exteriors,

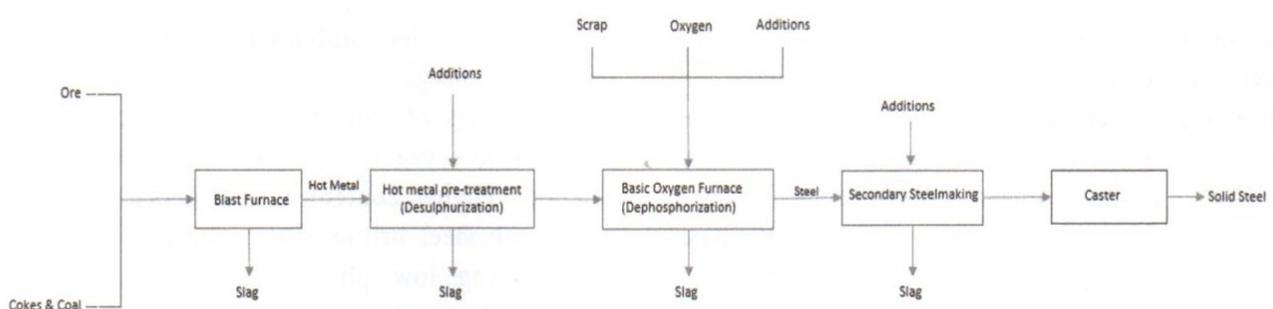


Figure 2. Diagrammatic outline of the steelmaking method.

gas pipelines etc. Phosphorus embrittles steels, lowering toughness and increasing the probability of fracture during manufacturing, fabricating, and service (Bloom T A 1990). Additionally, phosphorus impairs the ductility and toughness of goods like high strength plates and pipes, cryogenic steels, pressure vessel plates, etc. by causing intergranular segregation during continuous casting. (Marique and Nilles 1984)

In earlier times, phosphorus containment was not regarded as a great formidable task in steelmaking since iron ores having small phosphorus content were easily and cheaply available. Currently, the company XYZ of India under study has an operating regime in terms of various input parameters to control the phosphorus level in high silicon hot metal. In recent times, because of high iron ore prices (Iyengar 2020), lower-priced iron ores from sources with higher Phosphorus content are being used and this has made Phosphorus control an important activity during steel-making. It has been observed that when Silicon concentration rises, more Silicon oxide is produced, which leads to more slag formation and a lower phosphorus partition, both of which are detrimental to dephosphorization (Basu, Lahiri, and Seetharaman 2009). Dephosphorization is harmed by the rise in slag viscosity as the amount of the slag tends to grow. Therefore, less formation of slag and silicon oxide is preferable. Therefore, hot metal with low silicon content was considered for the study.

Hence, this work of authors provides an innovative method of process improvement to achieve the goal of low phosphorus content ($\leq 0.015\%$) in hot metal with low silicon ($< 0.4\%$) by optimizing the process parameters of the dephosphorization in the steel industry with the aid of Six Sigma (DMAIC approach).

2.1. Formation of project team structure

The initial way forward to problem resolving in this approach was in building a group of individuals connected to the operations involved. The XYZ company in India already had the human infrastructure as advocated by (Schroeder et al. 2008) and (Zu, Fredendall, and Douglas 2008) to facilitate the Six Sigma implementation to improve the process. This project team comprised the Head of the Black Belt (BB): – TQM Facilitation & CQA who was already trained in this field. The other team representatives were the Planning Manager, Maintenance Manager, and Quality Control Senior Engineer of the Basic Oxygen Steelmaking company. The BB was the chief/leader of the whole team and was in charge of the project to meet its objectives. The process owner of

the project was the head of the Basic Oxygen Steelmaking company. The main concern was to boost up the representatives to grow better in coordination with the BB to achieve the goals. The master black belt (MBB) was known as the Head of TQM & CQA and was also acknowledged as the Champion of the project. Roughly 300-350 DMAIC projects are carried out every year in this company.

3. Implementation of Six Sigma DMAIC methodology

Within Six Sigma structure, a team was set up for the project in the company and DMAIC approach was put forth to them for improvement of the dephosphorization process. The five phases of the DMAIC (define-measure-analyze-improve-control) are as follows:

3.1. Define

In the DMAIC methodology, it is the first phase that targets toward goals and scope of the undertaken project concerning necessities of end-consumers and also frames a goal-oriented process that caters to their requirements. The define phase consists of three components: prepare a Project charter with a business case, conduct a SIPOC analysis and define the problem statement.

Preparation of a business plan for Project Charter:

To prepare a business plan for the project charter, the redundant questions were put forth to team managers and they submitted their responses. This allowed the team members to extract the key aspects of the business case. The Project Charter (Figure 3) (Noori and Latifi 2018) was made, which outlined the project details and therefore facilitated the stakeholders to know the outlined goals and objectives, the timeline for completion, in-scope, out-scope, roles and responsibilities of team members, business case, etc. This made a common vision for the whole group which motivated them to achieve the stated goals.

Define the problem statement

Due to the usage of lower quality iron ores and the growing costs of iron ore (a 100% increase in the previous five years), dephosphorization of steel is essential. Higher content of phosphorus in the steel makes the steel brittle. An increase in demand for steel having low phosphorus content had been observed due to increase in its applications in automobile exteriors, thin sheets and gas pipelines for

Business Case	It has been taken as a departmental objective to establish the optimum phosphorus level ($\leq 0.015\%$) in the hot metal with low silicon ($< 0.4\%$ Silicon) by dephosphorization process using DMAIC techniques of Six Sigma.
Problem Statement:	To achieve low phosphorus content $\leq 0.015\%$ in Hot metal with low Silicon ($< 0.4\%$) resulting in end product steel having low phosphorus $\leq 0.015\%$ since the steel with low phosphorus content has good mechanical properties like high malleability and ductility, mainly suitable for use in automobile exteriors, gas pipelines etc.
Goal:	To control the phosphorus level to $\leq 0.015\%$ in the hot metal with low silicon ($< 0.4\%$) in dephosphorization process, thereby resulting in increasing phosphorus strike rate substantially more than current 52%.
In-Scope:	Achievement of Phosphorus level of $\leq 0.015\%$ in hot metal with low Silicon ($< 0.4\%$) by dephosphorization process in the steelmaking vessel. Constraints: Oxygen Blown, temperature, ore, scrap, lime, dolomite
Out of Scope:	Constraints: Slag, tap-tap time, basicity, re-blowing
Deliverables :	Enhancement of knowledge and understanding of the Dephosphorization process in Hot Metal and Standardization of Operating Procedures.
Project Status:	Black Belt Name: Head – TQM Facilitation & CQA Client(s) Impacted: Chief BOS(Basic Oxygen Steelmaking) plant Big Y Impacted: Phosphorus Strike Rate
Project Members:	Project Champion: Head of TQM & CQA Other Stakeholders: Maintenance Manager, Planning Manager, and Quality Control Senior Engineer of the Basic Oxygen Steelmaking plant

Project Timeline:	Project Plan				
	Phase (Expected) Completion Dates				
	May 2019	June 2019	July 2019	August 2019	Sept 2019
Define/Plan: 31.05.19					
Measure/Do: 30.06.19					
Analyse/Do: 31.07.19					
Improve/ Check: 05.09.19					
Control/Act: 30.09.19					

Figure 3. Project charter.

which, there was a necessity for process improvement in dephosphorization (Mukherjee and Chatterjee 1996). Further, high silicon content in hot metal brings about particularly higher slag impurities formation besides other disadvantages. Therefore, the managers of the company had taken an objective to establish the optimum phosphorus level ($\leq 0.015\%$) in the hot metal with low silicon ($< 0.4\%$) in the dephosphorization process by using DMAIC techniques of Six Sigma. The DMAIC principles had been suggested by the authors for problem-solving since the methods

for achieving the above objective and effects/problems associated with it were unknown (Breyfogle, Cupello, and Meadows 2001) to the steel managers. The procedures followed to achieve our goal to increase the phosphorous strike rate more than 52% (current), are delineated in sequence.

Conduct a SIPOC analysis:

During the execution of this project, the participants employed the SIPOC (Supplier-Input-Process-

Output–Customer) tool (Basu 2009) to analyze one or more current processes and how to modify and improve them. This SIPOC is a basic flowchart similar to the process map that defines and gives a clear understanding of the business process from the inputs to outputs involved. This prompts the participated members to identify all relevant elements: the inputs and the outputs which may be raw material, goods & services, suppliers including end-consumers internal or external to the organization. Thus, the focus is here for improvement and optimization of the process parameters involved in the dephosphorization process.

Figure 4 displays the SIPOC in respect of the existing dephosphorization process.

4. Measure phase

The main purpose of the Measure Phase is:

To understand the current status of the issue through data, define the performance standards and set the target, carry out the necessary measurement system analysis (Mandal 2012).

To understand the source of the problem and to discover the underlying causes of this problem and identify the appropriate methods to assess the nature of the problem. (Huang and Klassen 2016)

Several brainstorming sessions were held in the company to discover probable explanations for existing phosphorous strike rate based on the experience of the team members. Every member of the improvement team was permitted to ponder and contribute their thoughts in the brainstorming sessions. (Ishikawa 1982) points out that freedom of thought and involvement are the driving force behind determining and solving core causes of problems related to quality. A cause-and-effect relationship is studied to show and categorize the various causes responsible for the problems (Slack, Chambers, and Johnston 2010). The diagram developed for said relationship is often called the Ishikawa or the fishbone diagram which is an orderly method

of investigating the correlation between the effect and all probable causes (Ziegel et al. 1999) of the issues.

Once the above diagram was finished, the root reasons were identified and ideas were brought about for future development. The fishbone diagram was drawn with the help of expert knowledge and critical analysis of the actual process. The Figure 5 showed various root causes of end blow phosphorus strike rate. After all possible considerations, it was found out that for dephosphorization process, the two parameters (i.e., amount of oxygen blown and tapping temperature) had a direct impact on existing end blow phosphorus strike rate. As a result, the optimum range of above two identified parameters and their relation were studied in the DMAIC’s analysis phase using Mann-Whitney test.

Data was collected from the Oracle database of Basic oxygen furnace of the company under study. For our analysis, we referred to around 3000 heats of February–July 2018.

At initial, the data sanitization was done by removing the nulls and blanks from raw data (List wise elimination)(Peugh and Enders 2004). Then an extensive statistical data analysis was carried out to understand the relationship amongst various parameters affecting dephosphorization. The heats with hot metal having low Silicon content (< 0.4%) were filtered from data for our analysis as presented in Figure 6.

In (Figure 6), out of around 3000 heats, 191 heats were filtered containing silicon (<0.4%) that were considered for our study.

The members of the Six Sigma team also identified the internal process parameters that impacted the dephosphorization process. The various process parameters considered for the analysis from available data are shown in Table 1.

The controllable parameters found were the amount of oxygen blown, tapping temperature, amount of addition of ore, lime, dolomite and scrap, that can be controlled manually; while the uncontrollable

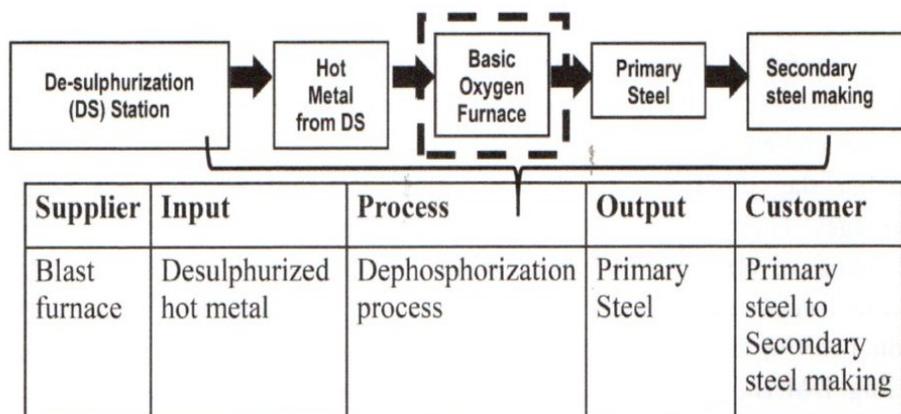


Figure 4. SIPOC for dephosphorization process.

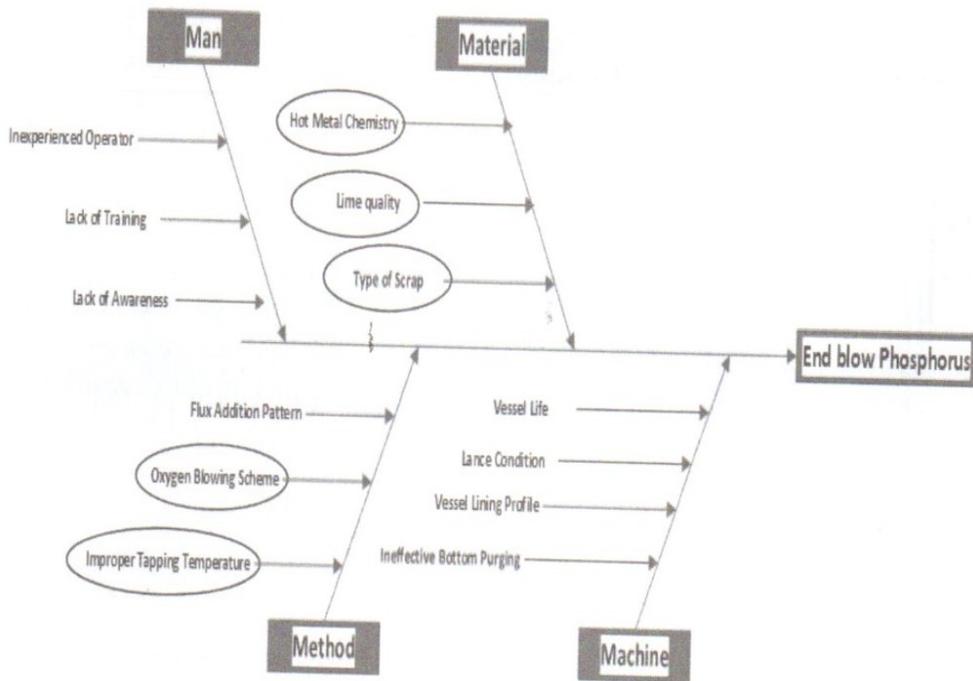


Figure 5. Fishbone diagram for the end blow phosphorus.
 Note: ^aRed circle shows potential cause

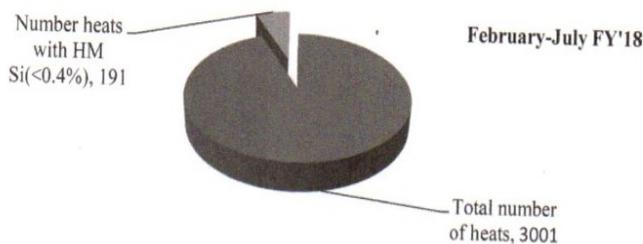


Figure 6. Number of heats considered for the study.
 Note: Heat – a batch of steel produced, HM Si – hot metal with silicon

parameters were the hot metal having Silicon and the end blow phosphorus, that cannot be controlled manually as they are already present naturally in ore.

5. Analyze

This stage in the DMAIC principles includes statistical study of the problem and reviewing the families of variation statistically (Anotony, Hoerl, and Snee 1987) to ascertain the important determinants influencing the output. In this study, the analysis was done through the statistical software STATISTICA Version-10 for the study of the relationship concerning the process parameters/variables of around 3000 heats for a period of February to July FY'2018 as available in Oracle database of the steel industry XYZ under study.

5.1. Stability test

The analysis of the sanitized data was done in a synchronized manner. The stability test was first done to check whether the data is stable. The Stable process will show a random behavior. This randomness was checked through Run Chart (Figure 7). The process is said to be stable if the p-value > 0.05.

Figure 7 infers from the data that for entire six months the process is unstable since trend and clustering each less than 0.05 for that period where as for small duration [example for 15 days], the process is stable.

5.2. Normality test

The normality test was conducted to verify whether the distribution of process data is normal. If the distribution of data is normal, the parametric statistics can be used that are based on this assumption (p value >0.05). Therefore, the Anderson Darling test as shown in Figure 8 was employed to examine the normality of data. This Figure 8 inferred that the p-value was less than 0.05, demonstrating the process data not satisfying normality. Hence, non-parametric tests were employed for analysis of the process data as the assumptions failed.

Table 1. Specific parameters affecting the Phosphorus Strike rate in dephosphorization process.

Probable causes	Problem or outcome
<ul style="list-style-type: none"> Hot metal having silicon Amount of oxygen volume blown Tapping temperature Addition of ore, addition of scrap, addition of lime, addition of dolomite 	End -blow phosphorus or phosphorus strike rate

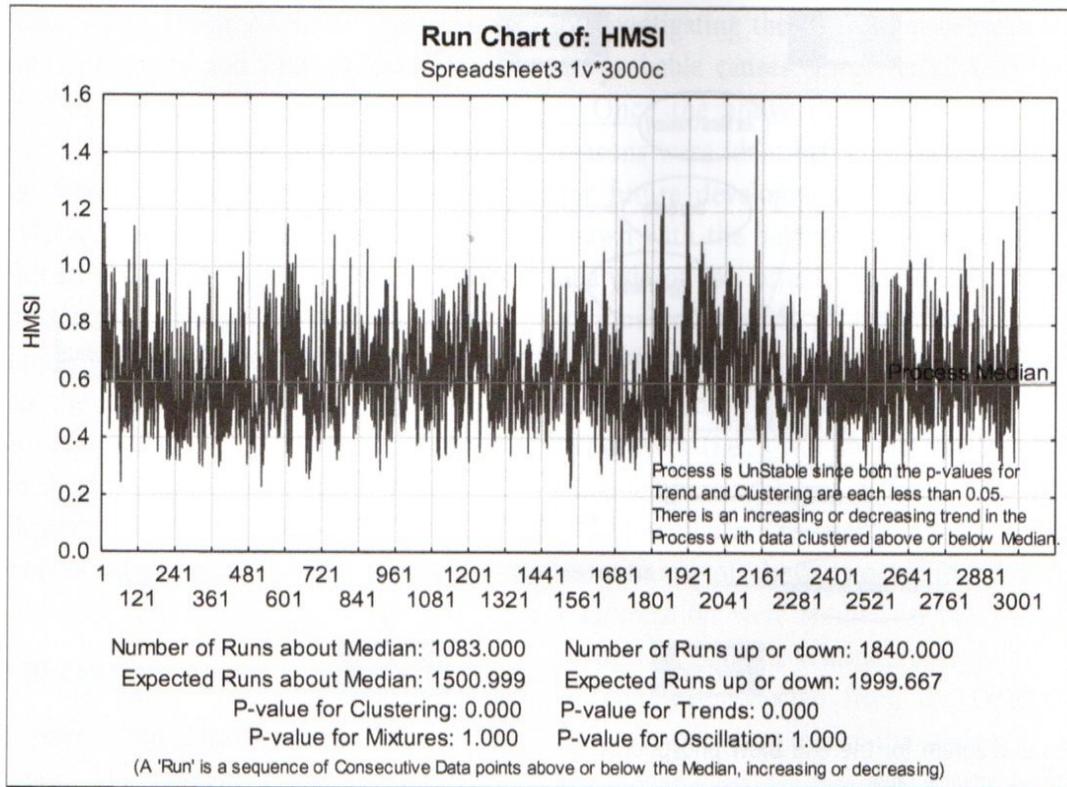


Figure 7. Stability test for data with 191 heats (low silicon content (< 0.4%) in hot metal) through Run Chart.
Note: HMSI: Hot metal with silicon

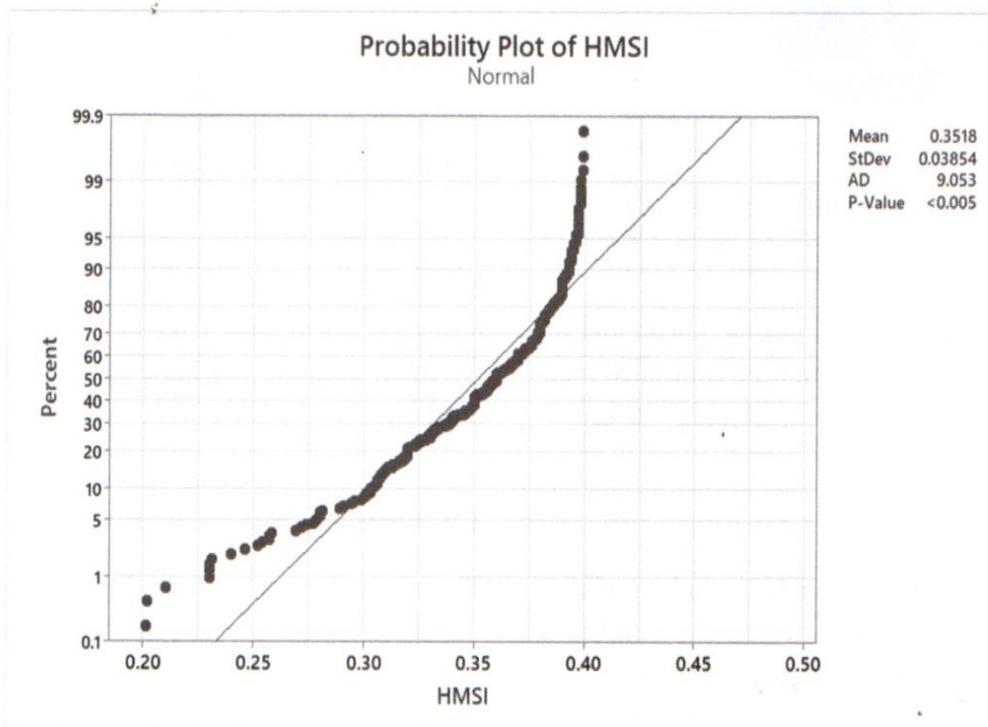


Figure 8. Normality test for the 191 heats with low Silicon content in hot metal (< 0.4%).
Note: HMSI: Hot metal with silicon

As the process data was found to be not normal in this case, the assumption failed restricting the application of linear regression. Henceforth, some data relating to end blow phosphorous was converted from continuous to discrete (categorical form). The end blow Phosphorus was divided into “good” and “Bad” on specific conditions.

If end blow Phosphorus $\leq 0.015\%$ then it is “Good” otherwise “Bad”.

5.3. Data analysis: Finding operating regime for the dephosphorization process

The steel company under study being very well established in steel sector since long, maintained large database of dephosphorisation process. These data were analyzed with the application of principles of each stage of DMAIC of Six Sigma which enabled to exclude the irrelevant data and zero in on appropriate data pertinent for this study on dephosphorization process. Those sorted out

Table 2. Summary results of hypothesis testing using Mann-Whitney test.

Sl.no.	Hypothesis testing	Calculated 'p' value	Result	Explanation
H ₁	There is no significant effect of the volume of oxygen blown in achieving dephosphorization.	0.000015	Null hypothesis Rejected	The p-value was < 0.05. This showed there was an effect of the volume of oxygen blown in dephosphorization.
H ₂	There is no significant effect of addition of dolomite in achieving dephosphorization.	0.675575	Null hypothesis Accepted	The p-value was > 0.05. So, there was no relation found for dolomite in dephosphorization
H ₃	There is no significant effect of addition of lime in achieving dephosphorization.	0.298168	Null hypothesis Accepted	The p-value was > 0.05. So, there was no relation found for lime in dephosphorization.
H ₄	There is no significant effect of addition of ore in achieving dephosphorization.	0.105462	Null hypothesis Accepted	The p-value was > 0.05. So, there was no relation found for ore in dephosphorization.
H ₅	There is no significant effect of addition of scrap in achieving dephosphorization.	1.15089	Null hypothesis Accepted	The p-value was > 0.05. So, there was no relation found for scrap in dephosphorization.
H ₆	There is no significant effect of tapping temperature in achieving dephosphorization.	***	Null hypothesis Rejected	The p-value was < 0.05. This showed there was an effect of tapping temperature in dephosphorization.

Note: level of significance $\alpha=0.05$ used in calculation. ***signifies p-value < 0.001.

applicable data were further examined with statistical tools like SIPOC analysis, stability test, normality test etc. relative to the phases of DMAIC which facilitated to identify significant process parameters including their optimal level that will make the processes efficient for increased production of low phosphorus steel and paved the way with the above simplification to find out the exact value of those parameters with further analysis on application of statistical methods like Mann-Whitney test and Regression analysis.

The cause-and-effect diagram was prepared by the team to narrow down the focus (Figure 4). Hypothesis testing using the Mann-Whitney test focused toward probing the process parameters and possible causes indicating their failure in achieving the goal, whether any alteration in the amount of oxygen blown, the range of tapping temperature, the addition of scrap, dolomite, lime, and ore affecting the dephosphorization process in hot metal with low silicon (<0.4%). The null and alternate hypotheses proposed to find out whether somewhat variation in the above process parameters resulted in any deviation in dephosphorization process. The box plot was used to figure out the perfect range for the parameters suitable to operate for the process thereby, optimizing the dephosphorization.

Here, the Mann-Whitney test was conducted considering the above process parameters for dephosphorization as independent variables, while the end blow Phosphorus considered as dependent variable with categorization good and bad. Once the hypotheses were formulated, the following analysis was done to test the statistical significance of each independent variable as shown in Table 2.

Hypotheses are assessed depending on the p-value (Moore, McCabe, and Craig 2009). The p-value signifies the rejection of null hypothesis if the p-value is less than

a significant value (Moore, McCabe, and Craig 2009). As per result (Table 2), it was also observed that there were some process parameters such as the amount of oxygen blown ($p=0.000015$) and the tapping temperature ($p = ***$), significantly impacting the dephosphorization process in hot metal having low silicon. Other process parameters like the addition of dolomite, lime, ore and scrap had no significant impact on the dephosphorization process in hot metal with low silicon.

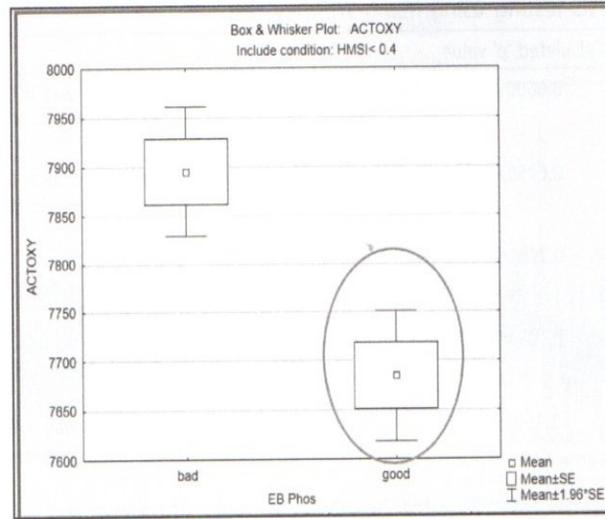
In view of the above statistical analysis and consequent proof, the next step was to determine the optimum tapping temperature and amount of oxygen to be blown that would result in the achievement of the required phosphorus level ($\leq 0.015\%$) in the dephosphorization process. The optimum amount of oxygen to be blown and the tapping temperature were summarized in the boxplot charts presented in Figure 9(a) and (b). When a certain process is not operating properly, the box plot aids in defining the difference or variation within it.

According to Figure 9(a), it was inferred that to achieve the end blow phosphorus ($\leq 0.015\%$ i.e., Good), lower volume of oxygen within the limit 7600 cc and 7750 cc should be blown to optimize the dephosphorization process.

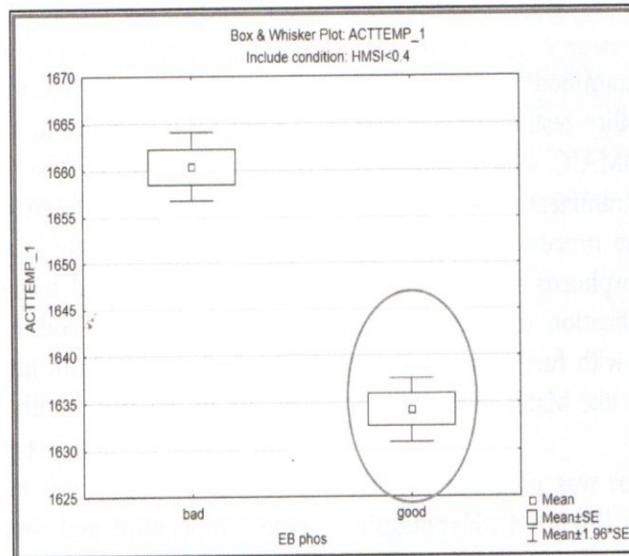
According to Figure 9(b), it was inferred that to achieve the end blow phosphorus ($\leq 0.015\%$ i.e., Good), favorable tapping temperature was found to be below 1640 °C. This suggested that lower temperature (<1640 °C) should be maintained as dephosphorization process is exothermic one.

5.4. Calculation of phosphorus strike rate

The Strike rate is a quality terminology that can be defined as the ratio of the number of heats finished



(a)



(b)

Figure 9. (a) Boxplot representation for the amount of oxygen blown. (b) Boxplot representation for the temperature.
 Note: EB phos: End blow phosphorus. HMSI: Hot metal with silicon, ACTOXY: actual oxygen volume blown in cc, ACTTEMP-1: actual tapping temperature in °C. *Green circle indicates the range of operation for achieving good phosphorus ($\leq 0.015\%$)

in a particular grade to the number of heats attempted in a particular grade (Source: TSE, Europe).

$$\text{Strike Rate} = \frac{\text{Number of heats finished in a particular grade}}{\text{Number of heats attempted in a particular grade}}$$

Strike Rate was calculated from the available data of the existing process of the steel industry XYZ of India under study as follows:

The number of heats for achieving steel grade of low phosphorous in its existing process was filtered from available process data of the steel industry. After identification of the appropriate heats, the strike rate or Turndown Phosphorus of its current process was calculated as follows:

Number of heats finished in a particular grade = 320 heats

Number of heats attempted in a particular grade = 620 heats

So, currently Strike Rate or Turndown Phosphorus = $320/620 = 0.516 \approx 0.52 = 52\%$ (approximately)

After the calculation of the current strike rate or Turndown Phosphorus, the improvement team suggested that the strike rate should be improved substantially from the current strike rate i.e., 52%. Therefore, there was a prerequisite for finding the relationship between the process parameters of dephosphorization to improve the current strike rate to (>0.52) in order to meet the suggestion, put forth by the improvement team.

From available process data, the number of heats for achieving required dephosphorization ($\leq 0.015\%$ i.e., good) were filtered satisfying the optimum parameters as obtained from the analysis of Figure 9(a) and (b) viz. the blown oxygen volume in the low range within the upper limit 7600cc to 7750cc corresponding to low tapping temperature maintained between the range of 1580°C and 1630°C.

EB phosphorus - Parameter estimate							
Distribution: BINOMIAL Link function: LOGIT							
Modelled probability that EB phosphorus = bad							
	Column	Estimate	Standard Error	Wald Stat.	Lower CL 95.00%	Upper CL 95.00%	Significant p value
Intercept	1	-150.18	21.30769	49.67687	-191.943	-108.418	0
ACTOXY	2	0.001	0.00057	2.7212	0	0.002	0.099024
ACTTEMP-1	3	0.087	0.01291	44.93542	0.061	0.112	0

Figure 10. Results of Logistic regression analysis.
 Note: ACTOXY: actual oxygen. ACTTEMP_1: Actual tapping temperature

The following analysis was undertaken to arrive at the desired result with much precision.

5.5. Regression analysis

Six Sigma provides more progressive techniques like regression analysis (example: logistic regression, curvilinear regression involving indicator variables), design of experiments, control charts and hypothesis testing which generally call attention to black-belt level (Tjahjono et al. 2010). Here, involving 191 heats, dichotomous dependent variable was End Blow Phosphorous (Good or Bad) and independent variables were Actual Oxygen Volume and Actual Tapping Temperature. The logistic regression equation is as follows:

$$P(X) = \frac{\exp(a + bX)}{1 + \exp(a + bX)}$$

Where; the independent variable, $X = x_1 + x_2 + \dots + x_n$

a, b are coefficients or parameter estimates

P(X) = Estimated Probability

Figure 10 illustrated that the coefficients (estimates) were $a = -150$, $b_1 = 0.001$, $b_2 = 0.087$. The independent variables x_1 , x_2 , were Actual Oxygen Volume (ACTOXY) & Actual Tapping Temperature (ACTTEMP_1) respectively.

Therefore, the logistic regression equation $P(X) = \frac{\exp(a + bX)}{1 + \exp(a + bX)}$ was formulated using the above data as below:

$$P(X) = \frac{\exp(-150 + 0.001x_1 + 0.087x_2)}{1 + \exp(-150 + 0.001x_1 + 0.087x_2)}$$

Then, using the regression results the Look-up table was designed for recommending the engineers and the managers of the steel industry XYZ of India under study for reference.

The look-up table (Figure 11) was constructed taking into consideration the significantly influencing

factors such as the amount of oxygen blown and the tapping temperature. The table had the green zone indicating the favorable zone for the better achievement of dephosphorization ($\leq 0.015\%$).

Then, the performance of the above model was reassessed by applying confusion matrix (Figure 12) since this tool helps in determining the accuracy of the above results with precision. The cases with resulting good end blow phosphorus ($\leq 0.015\%$) and those with bad end blow phosphorus ($> 0.015\%$) from the above model were verified with classification metrics of confusion matrix.

Figure 12 demonstrated that the accuracy of regression model was 78% for achieving good end blow phosphorus ($\leq 0.015\%$).

The confusion matrix found out the regression model for the case study as accurate and hence the results of the model carry significance for the study.

From the results of Regression model analysis, it was implied that for better achievement of dephosphorization ($\leq 0.015\%$), the blown oxygen volume should be in the low range within the upper limit 7600cc to 7750cc corresponding to low tapping temperature maintained between the range of 1580°C and 1630°C. By applying this result, significant number of finished heats could be obtained resulting in more turn down phosphorus as well as substantially increase in strike rate, more than current 52% for the required steel grade with phosphorous content ($\leq 0.015\%$).

6. Recommendations

The regression model (Figure 11) was recommended to the steel managers and process engineers of the company under study to comment on the suitability of the model suggesting parameters responsible for optimum dephosphorization of steel. All concerned person of the company mentioned that the regression

	Temp														
	1580	1590	1600	1610	1620	1630	1640	1650	1660	1670	1680	1690	1700	1710	
Oxy	6500	0.000693	0.001645	0.003902	0.009223	0.021647	0.049959	0.111098	0.229021	0.413838	0.626587	0.799525	0.904569	0.957498	0.981666
	6600	0.000761	0.001807	0.004285	0.010125	0.023734	0.054624	0.120746	0.246074	0.436854	0.648348	0.814197	0.912395	0.961117	0.983287
	6700	0.000836	0.001986	0.004706	0.011114	0.026017	0.059696	0.131107	0.263962	0.460148	0.66951	0.828025	0.919637	0.964537	0.984766
	6800	0.000919	0.002181	0.005169	0.012198	0.028513	0.065208	0.142214	0.282662	0.483613	0.690008	0.841026	0.926328	0.967821	0.986116
	6900	0.00101	0.002396	0.005676	0.013387	0.031241	0.071189	0.154095	0.302144	0.507153	0.709785	0.853218	0.932503	0.970445	0.987348
	7000	0.001109	0.002632	0.006234	0.014689	0.034221	0.077674	0.166776	0.322365	0.530661	0.728796	0.864625	0.938195	0.97303	0.988472
	7100	0.001219	0.002891	0.006845	0.016117	0.037474	0.084696	0.180278	0.343273	0.554034	0.747006	0.875276	0.943436	0.975395	0.989498
	7200	0.001339	0.003176	0.007516	0.01768	0.041023	0.092288	0.194617	0.364808	0.57717	0.764389	0.8852	0.948257	0.977557	0.990433
	7300	0.001471	0.003489	0.008252	0.019393	0.044893	0.100487	0.209805	0.386897	0.599973	0.780927	0.894429	0.952688	0.979533	0.991285
	7400	0.001616	0.003832	0.00906	0.021267	0.049109	0.109326	0.225847	0.409462	0.62235	0.796613	0.902998	0.956757	0.981338	0.992062
	7500	0.001775	0.004209	0.009946	0.023319	0.053698	0.118841	0.242737	0.432415	0.644218	0.811448	0.91094	0.96043	0.982987	0.992771
	7600	0.00195	0.004623	0.010917	0.025563	0.05869	0.129063	0.260466	0.455662	0.665501	0.825437	0.918291	0.963913	0.984493	0.993416
	7700	0.002142	0.005077	0.011982	0.028017	0.064115	0.140025	0.279013	0.479103	0.68613	0.838595	0.925066	0.96705	0.985867	0.994004
	7800	0.002353	0.005575	0.01315	0.030699	0.070004	0.151759	0.298348	0.502637	0.706049	0.850941	0.931357	0.969923	0.987121	0.99454
	7900	0.002585	0.006123	0.01443	0.033629	0.07639	0.164281	0.318431	0.526159	0.725211	0.862497	0.937139	0.972552	0.988265	0.995029
	8000	0.00284	0.006723	0.015833	0.036828	0.083306	0.177623	0.339212	0.549586	0.743577	0.87329	0.942464	0.974957	0.989308	0.995473
	8100	0.003119	0.007382	0.017369	0.040318	0.090786	0.191801	0.360632	0.572755	0.761119	0.883351	0.947364	0.977157	0.99026	0.995879
	8200	0.003426	0.008106	0.019052	0.044124	0.098866	0.206826	0.382621	0.595629	0.777821	0.892711	0.951867	0.979167	0.991128	0.996248
	8300	0.003764	0.008899	0.020894	0.048272	0.10758	0.222704	0.405101	0.618095	0.793671	0.901404	0.956003	0.981004	0.991919	0.996584
	8400	0.004134	0.009769	0.022911	0.052788	0.116962	0.239432	0.427987	0.640067	0.808668	0.909464	0.959799	0.982682	0.99264	0.99689
	8500	0.00454	0.010724	0.025117	0.0577	0.127046	0.257002	0.451184	0.661467	0.822819	0.916926	0.96328	0.984214	0.993297	0.997169
	8600	0.004986	0.01177	0.027529	0.06304	0.137863	0.275394	0.474596	0.682227	0.836135	0.923824	0.96647	0.985613	0.993896	0.997423
	8700	0.005476	0.012918	0.030166	0.068837	0.149444	0.29458	0.498121	0.702286	0.848635	0.930193	0.969391	0.986889	0.994441	0.997654
	8800	0.006014	0.014176	0.033047	0.075125	0.161815	0.314523	0.521653	0.721596	0.86034	0.936066	0.972066	0.988053	0.994938	0.997864
	8900	0.006604	0.015554	0.036192	0.081936	0.175	0.335174	0.54509	0.740117	0.871277	0.941477	0.974513	0.989116	0.995391	0.998056
	9000	0.007251	0.017064	0.039629	0.089306	0.189016	0.356476	0.568329	0.757819	0.881476	0.946455	0.97675	0.990084	0.995804	0.99823

Figure 11. The Look-up table (regression model) as per the results derived from regression equation.
 Note: Oxy: oxygen volume blown in cc. Temp: tapping temperature in °C

Classification of cases			
Odd ratio: 11.863636			
Log odds ratio: 2.473478			
	Predicted Bad	Predicted Good	Predicted Correct
Observed: bad	72	22	76.595
Observed: good	24	87	78.378

Figure 12. Results of confusion matrix.

model applied in this study could be of great advantage since it was based on up-to-date statistical analysis of data of their company in contrast to old method of guesswork and assumption of hypothesis, the model would be useful to their company since it being very old and reputable one in steel sector possessed a lot of data of their dephosphorization process and the result of this analysis using relevant data from their data base producing efficient insight into the process and the outcome of the study maintaining particular range of tapping temperature and blown oxygen volume to attain the desired level of dephosphorization (<=0.015%) in their BOF process would facilitate to work smartly, the ability of this powerful statistical

tool to select from the data of the process, the key dependent variable (End Blow Phosphorous Good or Bad) and independent variables (Actual Oxygen Volume and Actual Tapping Temperature) and ascertain methodically with the application of regression equation, the correlation between them and assess the optimum level of independent variables/parameters to attain the goal of dephosphorization (<=0.015%) would be of great interest when executed in their company and the application of classification metrics of confusion matrix on the regression model establishing the accuracy of this model for targeted dephosphorization (<=0.015%) impressed them and the model was admitted to be innovative and predictive for future success.

The result of this study showed that the condition of optimization for the improved dephosphorization ($\leq 0.015\%$ i.e., good) in hot metal with low Silicon content ($< 0.4\%$) was achievable by maintaining the optimum tapping temperature in low range between 1580°C and 1630°C and blown oxygen volume in the lower range within the upper limit 7600cc to 7750cc . In case the temperature increased beyond certain values ($> 1630^{\circ}\text{C}$), a lower oxygen volume was recommended to be blown as the dephosphorization process is an exothermic reaction.

The engineers and managers of the company analyzed the recommendation as stated above and opined that the aforesaid results using Six Sigma would be highly beneficial to the company in terms of saving precious energy due to its uniqueness of operating in the regime of lower tapping temperature and lower blown oxygen volume and encouraging effect on production of quantity including quality of final product low phosphorous grade ($\leq 0.015\%$) steel efficiently vis-a-vis the current procedure of multiple pretreatments of hot metal and elimination of rejections at each stage involving consumption of a lot of energy. This opinion had been put up to Technology and Research & Development Department of the company for approval.

7. Conclusions and way forward

High phosphorous content in steel makes it brittle and less ductile making unsuitable for use mainly in thin sheet, automobile exteriors, deep drawn pipelines etc. Several studies have been undertaken worldwide to find out better process dynamics, thermodynamics, kinetics, methods, time frames including chemical, statistical and mathematical models to achieve improved dephosphorization in end product steel from various grades and qualities of iron ore with focus on reduction of several steps and processes involved as well as associated costs.

Over the last two to three years employing Six Sigma for steel industries has become a topic of exploration by a number of scholars and six sigma practitioners. The objective of their analysis is to demonstrate that steel industries may also be profited by using Six Sigma methodology of management. In this context, the study was conducted in a renowned steel company of India to improve the dephosphorization process in its integrated Basic Oxygen Furnace (BOF) route for reducing the content of phosphorous in its end product steel since high phosphorous content in steel makes it brittle and less ductile making unsuitable for use mainly in thin sheet, automobile exteriors, deep drawn pipelines etc. Further, low quality iron ore is used by the industry since availability of good quality iron ore is depleting globally and their prices soaring.

In this scenario, the study has been undertaken in discussion with the company concerned XYZ of India, with a goal set to reduce the phosphorous content to $\leq 0.015\%$ in hot metal from BOF having low silicon $< 0.4\%$. The company data base of production heats was queried to identify batches with low silicon and these were analyzed by applying Six Sigma DMAIC methodology and it was concluded that Six Sigma proved itself to be an innovation strategy, leading to the identification of some critical process parameters and providing tools to find optimal values of the process parameters.

The study identified statistically the parameters like tapping temperature and blown oxygen volume, significantly influencing phosphorous content in resulting hot metal having low silicon $< 0.4\%$ from BOF and recommended an operating regime of lower oxygen volume blown in the low range within the upper limit 7600cc to 7750cc corresponding to low tapping temperature maintained between the range of 1580°C and 1630°C for efficient dephosphorization to meet the goal of production of low phosphorus ($\leq 0.015\%$) grade steel.

This finding of a particular range of tapping temperature and blown oxygen volume of this study has greater benefit over those factors maintained in the extant process since this new innovation involves very less rigorous methods and also fewer steps and thereby eliminates detrimental effects of slag impurities formations in multiple steps. The data-driven DMAIC facilitated to upgrade the process performance through the results of the regression model. Thus, Six Sigma is found to be a quality and productivity development targeted at the steel industry.

The production team of the steel industry admitted this venture of application of Six Sigma in steel industry as a great ingenuity and forerunner of new vistas for improving various method. The result of this research study would be implemented in the industry as and when the same is approved by the Technology and Research & Development Department of this Steel industry.

The key take-away of this research was identification of some critical process parameters of dephosphorization and providing an operating regime suitable for augmenting the phosphorus strike rate substantially more than 52% (current). The other significant learning was enthusiastic participation of their top executives in such initiative. Only for senior managers' involvement and dedication, any improvement initiative would be successful in reality. In this direction, the management could ensure involvement of all concerned connected with the process in the brain storming session that led to find out the probabilities affecting the process.

The novelty of this study is that it suggests an approach employing Six Sigma for the steel industry, for efficient production of improved quantity and quality steel with

low phosphorous content $\leq 0.015\%$ by maintaining lower tapping temperature (between 1580°C and 1630°C) as well as lower volume (7600cc to 7750cc) of blown oxygen resulting in resource optimization on energy front in contrast to the existing process of frequent pretreatment of hot metal and removal of rejection at each stage with consumption of substantial energy. The description and results of this study may be referred to as ideal when trying to deal with optimization of similar processes later.

Disclosure statement

No potential conflict of interest was reported by the authors.

Definition of terms used.

For the purpose of clarification, the important terms used in this study have been defined.

The following terms are:

Tapping: A technique of tapping a steelmaking furnace that involves identifying the desired level of steel to be obtained in a ladle and estimating the weight of molten steel that will be present when the required level is reached after transferring molten steel from the furnace to the ladle.

Desulphurization: To remove most of the sulfur from hot metal before it enters the BOF (Basic oxygen Furnace).

Heat: A batch of steel produced

Strike rate: The Strike rate is a quality terminology that can be defined as the ratio of the number of heats finished in a particular grade to the number of heats attempted in a particular grade.

End blow phosphorus: The phosphorus content of molten steel at the end point of BOF during blowing (Basic Oxygen Furnace).

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