

University of Wales Trinity Saint David

Manufacturing Systems and Quality – On the Define and Measurement Stages of Testing Coke Strength after Reaction (CSR)

BEng Material Science – M5X01177

Table of Contents

1	INTRODUCTION	4
1.1	COKING METHODOLOGY.....	4
1.2	THE IMPORTANCE OF COKE TO THE IRON MAKING PROCESS	5
1.3	ANALYSING COKE STRENGTH AFTER REACTION (CSR).....	5
1.4	MOTIVATIONS FOR CSR TESTING	6
1.5	PROBLEM FOCUS AND PURPOSE	6
1.6	INVESTIGATING THE EFFECTIVENESS OF SIX SIGMA METHODOLOGIES	7
2	DEFINE STAGE	7
2.1	PROBLEM STATEMENT	7
2.2	SIPOC PROCESS MAPPING.....	10
2.3	THE VOICE OF CUSTOMER	12
2.4	CRITICAL TO QUALITY FACTORS	13
2.5	PROJECT SCOPE.....	13
2.6	PROJECT CHARTER.....	14
3	MEASUREMENT STAGE	15
3.1	IDENTIFYING MEASUREMENT AND VARIATION.....	15
3.2	DETERMINING DATE TYPES	16
3.3	DEVELOPING A DATA COLLECTION PLAN.....	17
3.4	PERFORMING MEASUREMENT SYSTEM ANALYSIS (MSA)	19
3.5	COLLECTING DATA AND ASSESSING CAPABILITIES	21
3.6	FMEA (FAILURE MODE AND EFFECTS ANALYSIS) & RISK EVALUATIONS	24
4	CONCLUSIONS.....	24
4.1	FINDINGS	24
4.2	ERROR.....	25
4.3	RECOMMENDATIONS.....	25
5	WORKS CITED.....	26

Figure 1 A basic process flow of coal to coke transition (Michael Hein, 2012)	4
Figure 2 Basic diagram of a by-products coke oven (Michael Hein, 2012)	4
Figure 3 Trends of coke and steel production over time (Michael Hein, 2012)	5
Figure 4 The coking of a single coal particle (Gray, 1989)	5
Figure 5 Example of daily automated email sent to customers with CSR results (see blue line for trends)	8
Figure 6 Example 1 of CAR raised in response to questionable CSR results	8
Figure 7 Example 2 of CAR raised in response to questionable CSR results	8
Figure 8 SIPOC diagram for CSR testing	11
Figure 9 A segment of the morfa coke ovens SLA agreement	12
Figure 10 (Product Plan, 2020)	13
Figure 11 Cause and Effect Diagram	14
Figure 12 Cause and Effect Matrix	14
Figure 13 Project Charter	15
Figure 14 Coke Preparation Flow Chart	18
Figure 15 MSA study	20
Figure 16 Normal distribution for CSR data	23

Table 1 Criteria for multiple determinations (British Standards Institution, 2018)	6
Table 2 Summary of CAR's raised for non-conformant CSR results reported by the raw materials dept over a 10-month period	9
Table 3 A comparison of data types (Donges, 2018)	16
Table 4 Considerations about creating data collection plan.	17
Table 5 Data Collection Plan.	17
Table 6 Data Collection Plan	19
Table 7 Summary of Capability Analysis	21
Table 8 Raw data	22
Table 9 Table of calculations	22
Table 10 FMEA Tool and Risk Evaluation	24

1 Introduction

1.1 Coking Methodology

Metallurgical coke is integral in blast furnace iron making, providing fuel, structural support and a reduction agent. Raw materials imported to Tata Steel create slab steel; these raw materials, specifically coal, have unknown and unpredictable chemical compositions. The ironmaking process requires coal to undergo refinement before entering the blast furnace.

One coal rarely meets all specifications, combining coal mixtures create ideal blends before transportation via conveyor belts to the coke ovens. Here, vertical insulated ovens heat the coal blends in the absence of oxygen at 1200 -1300°C for approximately 18 hours; producing coke and removing volatile compounds. Following the coking cycle, red hot coke is pushed from the ovens (discharged), immediately water quenched to achieve desirable properties. This is known as ‘coking’ and the reaction taking place, carbonisation.

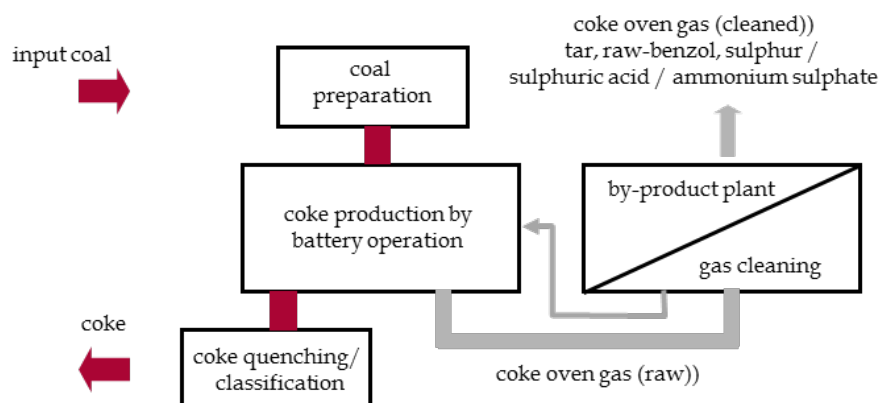


Figure 1 A basic process flow of coal to coke transition (Michael Hein, 2012)

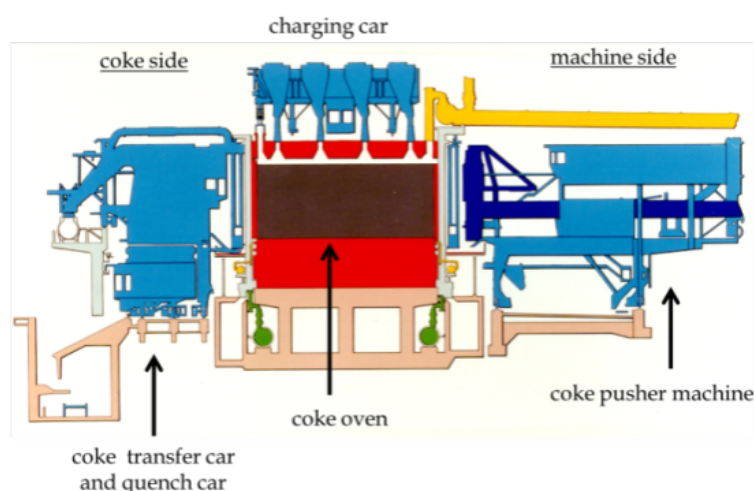


Figure 2 Basic diagram of a by-products coke oven (Michael Hein, 2012)

“The first rectangular or retort coke ovens were constructed in 1830 in Germany and, in 1835, retort coke was produced by William Firmstone in Pennsylvania. The greatest growth in the coking industry developed when coke replaced charcoal as the fuel for the blast furnace.” (Gray, 1989)

1.2 The importance of Coke to the Iron Making Process

65% of global steel production uses an iron blast furnace, of which coke is a necessary reducing agent. Governed by the demand of steel, since 1990 coke production has increased by 70%. (Michael Hein, 2012)

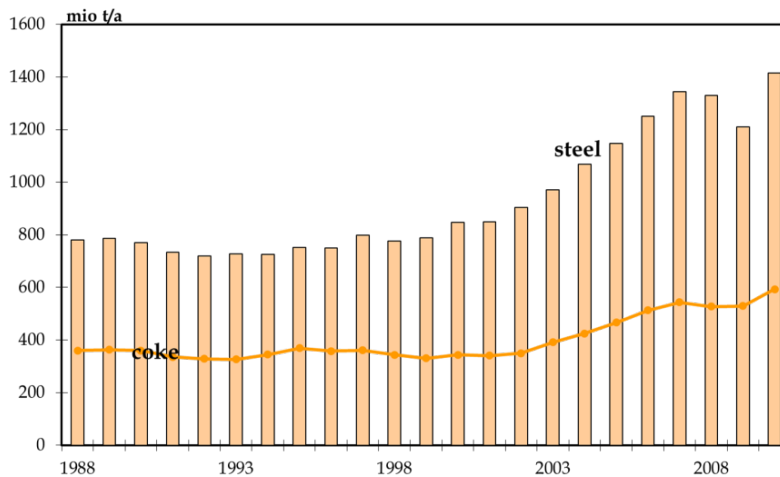


Figure 3 Trends of coke and steel production over time (Michael Hein, 2012)

There are advantages to using coke as opposed to unrefined coal in iron making:

- Impurities are burnt off, producing an almost pure form of carbon.
- Coked-coal deposits less ash. (Excessive ash over 10% reduces furnace temperatures).
- Reduces chances of incomplete combustion in the blast furnace.
- Coking softens, liquifies and resolidifies as more porous lumps, aiding gas transfer during iron making. (Xing, 2019)

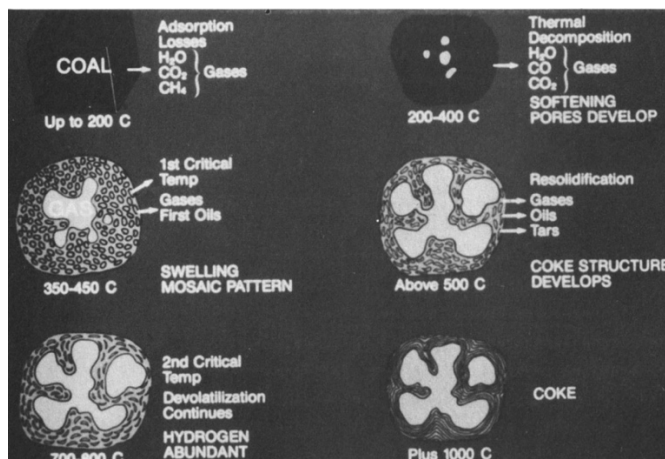


Figure 4 The coking of a single coal particle (Gray, 1989)

1.3 Analysing Coke Strength after Reaction (CSR)

The coke must be high strength to support a burden and pure to undergo chemical reactions without contamination.

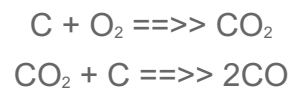
(M.A. Dí ez, 2001)

Testing is in accordance to the international standard BS ISO 18894:2018; CSR evaluates a dried composite of coke (sized 19.0–22.4mm) collected over 48 hours of production. The test specimen is heated at 1100°C in a nitrogen atmosphere for exactly 2 hours, the reaction vessel is cooled to 50°C and the specimen treated in a specialised tumbler for 600 revolutions. CSR is determined by measuring the retained weight after being sieved through 9.5–10.0mm apertures, calculated as a percentage of the samples original weight.

1.4 Motivations for CSR Testing

Coke strength predictions based on representative samples minimises empirical coke testing, allowing evaluations on limited sample sizes, permitting premeditated blending for optimum conditions.

Carbon in coke reacts with oxygen in the furnace producing carbon dioxide in an exothermic reaction. More carbon from coke then reacts with carbon dioxide, creating carbon monoxide, a vital reducing agent to make iron. The efficiency of reactions is based on chemical compositions, pore diffusion and temperature; prior knowledge of coke strength allows production units to strategically blend coals, producing cokes with ideal properties. (Gray, 1989)



1.5 Problem Focus and Purpose

18894:2018 states regular checks of apparatus and method is crucial to verify test results. (British Standards Institution, 2018)

To meet this criteria, internal standards are developed and tested weekly;
“Results of duplicate tests based on the same representative analysis samples, carried out in the same laboratory by the same operator with the same apparatus within a short period of time shall not differ by the values shown in table” (1.0 – 2.0 in this case).
 (British Standards Institution, 2018)

CRI	Range $ \bar{X}_1 - \bar{X}_2 $		
	A	B	C
≤ 10	—	—	—
$>10 \leq 20$	2,0	2,5	2,7
$>20 \leq 30$	2,5	3,2	3,5
$>30 \leq 40$	3,0	4,0	4,5
$>40 \leq 60$	3,5	5,0	5,5
>60	—	—	—

Table 1 Criteria for multiple determinations (British Standards Institution, 2018)

A minimum of two tests shall be completed for a paired result, should the repeatability limit be exceeded, additional testing is required to obtain repeatable results. Improving the validity of standard testing, achieves customer confidence and higher quality results.

1.6 Investigating the Effectiveness of Six Sigma Methodologies

American engineer Bill Smith introduced the lean six sigma DMAIC (define, measure, analyse, improve, control) improvement technique to improve quality in the industrial sector. The Define and Measurement methodologies, provides clarity and transparency, finding effective solutions. (Monika Smętkowska, 2018)

The tool is effective in finding process defects and providing feasible solutions. Numerous case studies support the methods successes; reducing manufacturing costs, consistent quality, reducing rejection rates and increasing profitability. (R.S.Barot, 2020)

In some cases, the method has been ineffective, suggesting that it fails to exploit task specific knowledge. The report advises that despite the approach using good statistical techniques, the problem diagnosis isn't efficient. (Jeroen de Mast, 2012)

“Methodological support for the identification of potential problem causes is offered as an incoherent and poorly structured collection of techniques, without strategic guidance to ensure efficiency of the diagnostic search.” (Jeroen de Mast, 2012)

Both the methods' strengths and limitations will be considered going forward.

2 Define Stage

The define stage establishes understanding of the problem, identifies affected customers and their expectations. (M.T.Pereira, 2020)

2.1 Problem Statement

The problem statement outlines the initial scope, clearly defining and quantifying the problem.

Technical Laboratories are responsible for providing material analysis, determining process conditions for steel production. The raw materials department provides a service to the coke ovens and blast furnace to deliver timely and accurate analysis of coke specimens.

The frequency of CSR testing is daily, automated emails are issued to all customers declaring results (figure 5). To verify result accuracy, a weekly standard test is run in accordance with 18894:2018.

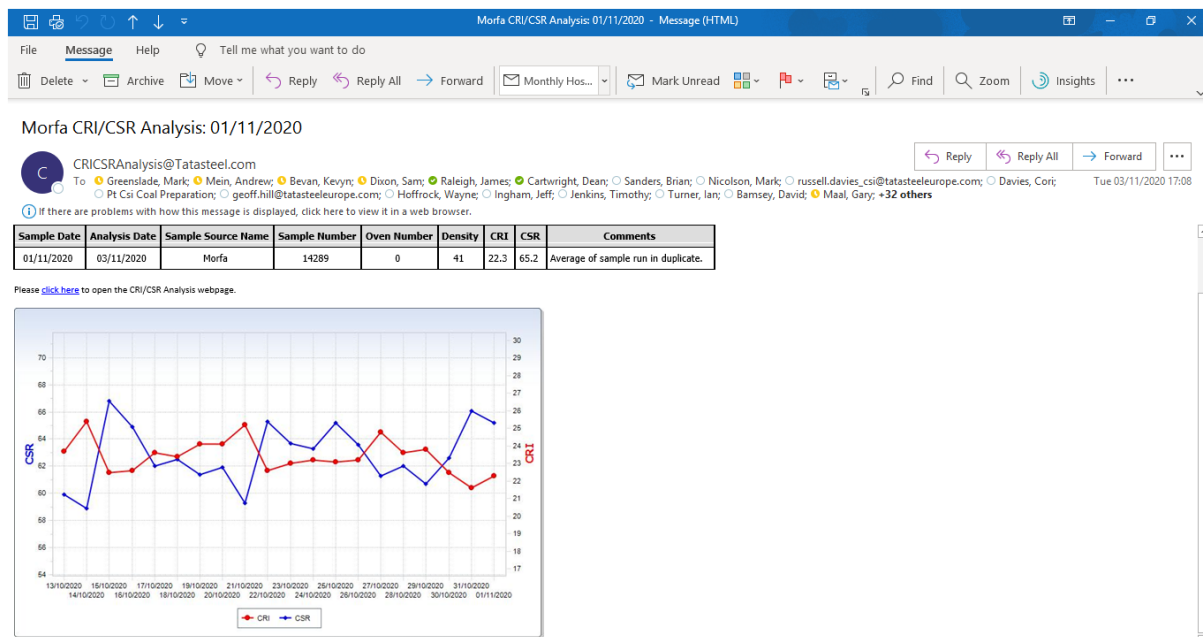


Figure 5 Example of daily automated email sent to customers with CSR results (see blue line for trends)

Customers report non-conformances and service level agreement (SLA) deviations via an internal corrective action reporting (CAR) database. Slow, inaccurate analysis has significant quality implications leading to economic loss.

Numerous CAR's have been submitted for the raw material labs attention; a large percentage surface similar issues, a loss of confidence in CSR results where there are increased numbers of 'questionable' and 'inconsistent' results. Numbers of similar reports raised increases with time. Table 2 summarises reports raised since 01/01/2020, (examples in figure 6 and 7).

Summary

Corrective Action Report details :

- Raised by : Paul DICKINSON, Area Coke Ovens
- Report initiated as Customer Complaint, corrective action type Analysis Query on 14/02/2020
- Allocated to Jamie WATERS (Technical Laboratories / Sampling + Raw Materials)
- **Process** : CSR testing
- **Concern** : First CSR run 57% ave. Second pair 62% ave for same sample - very different results
- **Full Description** : Same CSR sample was run 4 times. First pair gave very different result to second pair. Unsure which result is correct to be able to follow up appropriately

Figure 6 Example 1 of CAR raised in response to questionable CSR results

Summary

Corrective Action Report details :

- Raised by : Jamie WATERS, Area Coke Ovens
- Report initiated as Customer Complaint, corrective action type CAR on 17/07/2020
- Allocated to Rob MARTIN, Jamie WATERS (Technical Laboratories / Sampling + Raw Materials)
- **Process** : CSR reporting
- **Concern** : CSR results reported on system, despite being outside repeatability
- **Full Description** : This week a CSR result was reported on system, despite being outside of tolerance for repeatability. If a third test is to be run, results can be communicated by email or verbally, but should not be uploaded as it can cause confusion.

Figure 7 Example 2 of CAR raised in response to questionable CSR results

Date CAR Raised	Report Originator	Report Summary	Consequence
21/01/2020	J Waters (<i>raw materials manager</i>)	CSR value below minimum tolerance.	Retest actioned.
14/02/2020	P Dickinson (<i>coke ovens production manager</i>)	CSR values vary greatly between 4 tests on same sample.	Validity confirmed by running 4 tests again.
28/02/2020	S Jones (<i>blast furnace director</i>)	CSR value unrealistically high.	Additional standard run to verify result.
02/03/2020	R Taylor (<i>lab shift manager</i>)	CSR values vary between numerous tests on one sample.	Validity of correct results confirmed through retests.
09/03/2020	P Dickinson (<i>coke ovens production manager</i>)	CSR trial results differ to expected values.	Trial run again on different product.
21/04/2020	P Dickinson (<i>coke ovens production manager</i>)	CSR value below minimum tolerance.	Retest actioned.
25/04/2020	P Dickinson (<i>coke ovens production manager</i>)	CSR value below minimum tolerance again.	Retest actioned and value ok.
05/05/2020	J Waters (<i>raw materials manager</i>)	CSR standard value out of tolerance.	Rerun standard test to verify.
18/05/2020	S Jones (<i>blast furnace director</i>)	CSR trial values differ from predicted results.	Trial run again.
29/05/2020	J Waters (<i>raw materials manager</i>)	CSR value below minimum tolerance.	Retest actioned.
04/06/2020	R Taylor (<i>lab shift manager</i>)	CSR standard out of tolerance.	Standard rechecked.
08/06/2020	R Taylor (<i>lab shift manager</i>)	CSR standard out of tolerance.	Standard rechecked.
01/07/2020	M Phillips (<i>labs section manager</i>)	CSR value below minimum tolerance.	Retest actioned.
17/07/2020	J Waters (<i>raw materials manager</i>)	CSR value out of tolerance.	Retest carried out and reported.
22/07/2020	J Waters (<i>raw materials manager</i>)	CSR standard out of tolerance.	Standard rechecked.
09/08/2020	M Phillips (<i>labs section manager</i>)	CSR values abnormally high on numerous tests.	New tests requested and rechecks complete.
02/09/2020	R Taylor (<i>lab shift manager</i>)	CSR standard out of tolerance.	Standard rechecked.
14/10/2020	S Jones (<i>blast furnace director</i>)	CSR values vary across numerous tests on same sample.	Retest carried out on new sample to verify.
22/10/2020	S Jones (<i>blast furnace director</i>)	CSR values unreliable due to variation on same sample.	Retest carried out on new sample to verify.

Table 2 Summary of CAR's raised for non-conformant CSR results reported by the raw materials dept over a 10-month period

The problem factors have been consolidated, determining a final problem statement;

‘The customers, the morfa coke ovens and blast furnace departments are dissatisfied with the reliability of daily CSR test data, customers don’t trust the data; resulting in an average of 1.9 CAR’s raised per month. Weekly standard tests identify outliers exceeding two standard deviations, proving ineffective in detecting machine variation.’

2.2 SIPOC Process Mapping

Process mapping shows process steps in a simple manor to visualise bottlenecks, areas of weakness and non-value-added steps. SIPOC (representing supplier, input, process, outputs, customers) process mapping focuses on steps and consequences critical to quality (CTQ). Figure 8 is SIPOC process map for CSR testing. (Attard, 2014)

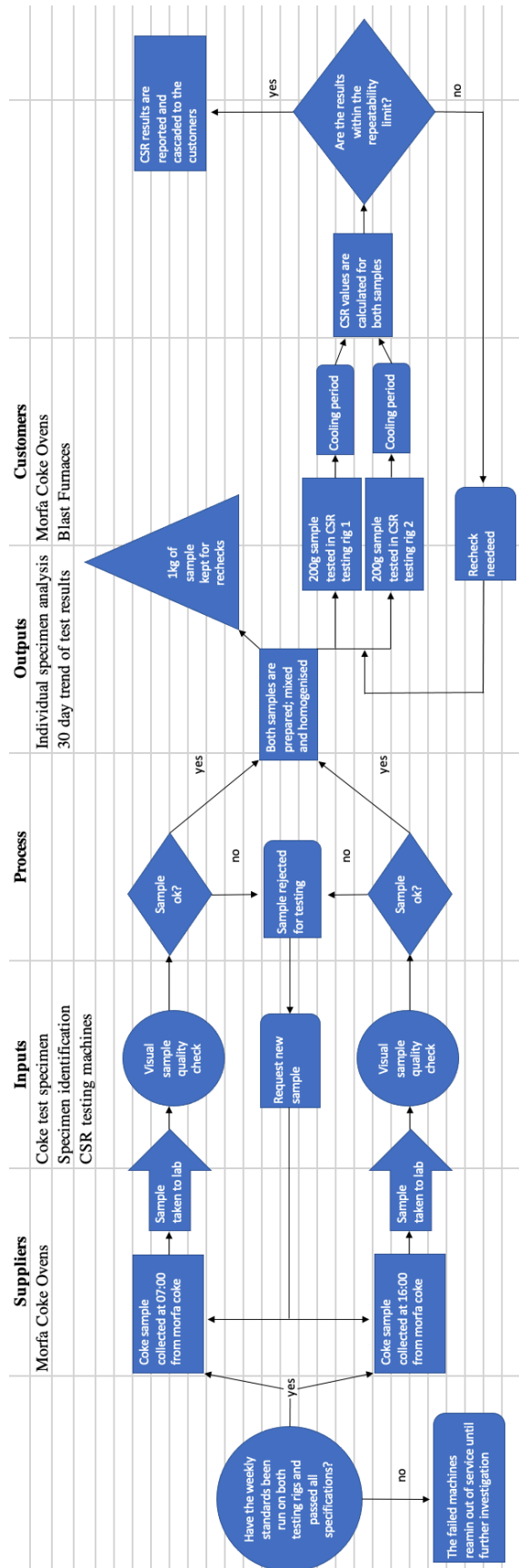


Figure 8 SIPOC diagram for CSR testing

Process Map Symbol Key	
	Process Step
	Delay
	Quality Check
	Storage
	Decision
	Transport

A significant non value added step is the preparation and storage of 1kg samples retained for retesting. Time is spent preparing and storing coke specimens that are only used in the event of a failure.

Quality checks prove to be another non value added step where samples fail and further resampling is required.

For failed test results, time is lost during the initial test, which takes 4 hours with additional cooling time.

Process delays have been identified, samples not meeting visual quality checks are resampled, lengthening the time for analysis.

Tested samples that do not meet standard specifications require a retest, lengthening analysis time.

The samples are air dried to 50°C which is time consuming compared to machine aided methods.

2.3 The Voice of Customer

Customers are recipients of products or services, categorised into internal and external. The voice of the customer (VOC) refers to a learning strategy aiming to obtain direct customer feedback to improve performance.

Here, the customers voices are captured through regular casual contact via email and Skype calls, and formally through monthly SLA meetings. Communication methods are considered close, as the service is directly in contact with customers, and effective due to accurate documentation of meetings on a regular basis. Using VOC methodologies allow for efficient determination of key issues and specifies customer expectations.

SLA's between customers and providers establish a reasonable time to test; the agreed time to deliver CSR results is 5.25 hours or less (figure 9).

TATA Strip UK Associated Document	
Title	Morfa Coke Ovens Service Level Agreement
Document	
3. Scope of Services	

Supplier (Laboratories):

1. Sampling and testing within 5.25 hours as agreed in SLA meeting.
2. Sign in and out at agreed locations.
3. Reporting of test results.
4. Safe disposal of all materials post-testing
5. Provision of correct sampling equipment where MCO required to provide samples.
6. Performing of re-checks where laboratory process must be ruled out as the root cause.
7. Provision of technical support for tar analysis equipment.
8. Provision of ad hoc testing through use of the ad hoc booking system.
9. Notification of disruption or likely disruption to service as soon as it is perceived.
10. Notification of corrective actions and timelines following disruption to service.
11. Root cause analysis within 2 weeks and completion of CARs within one month of initiation or action plan agreed in SLA meeting.
12. Notify Morfa shift team of any issues as they arise.

Figure 9 A segment of the morfa coke ovens SLA agreement

2.4 Critical to Quality Factors

To ensure customer satisfaction and undergo continuous development, all CTQs must be considered and prioritised. (Prasher, 2014)

A prioritisation framework, developed by Dr. Noriaki Kano in 1984 known as the Kano model, systematically prioritising features based on likelihood of customer satisfaction. (Product Plan, 2020)

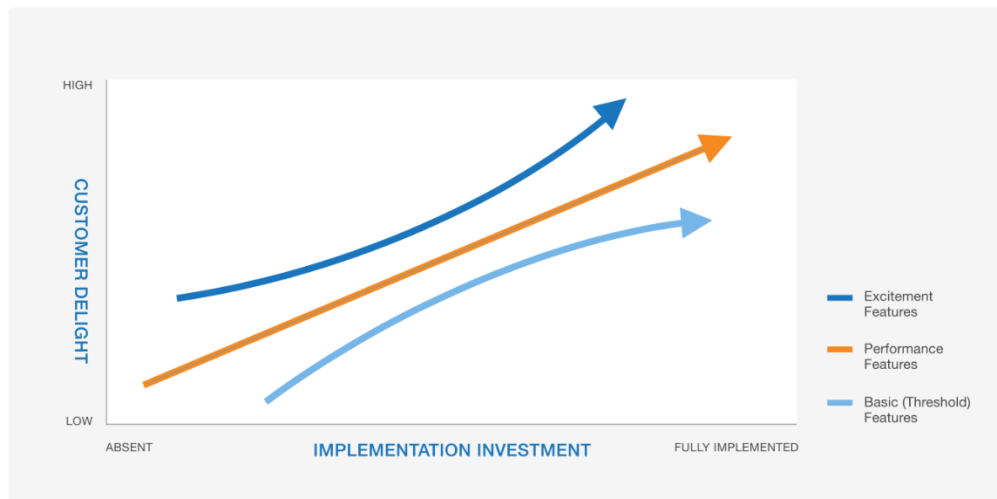


Figure 10 (Product Plan, 2020)

SLA meeting feedback identifies priority services for customers, the identified CTQ is the delivery of accurate results within the agreed timeframe. The validity of the data is being questioned, so the testing and monitoring of standard testing on CSR rigs will be measured.

2.5 Project Scope

Project scope outlines to what extent target specific areas will be measured; identifying if problems are within the teams' control and if improvements can be made within the timeframe, determining adequate resources.

To determine the causes and effects, the breakthrough ' $y = f(x)$ ' function can be utilised where y represents outcome, f is function and x is input. Numerous functions of x (causes such as quality) will result in y (the output). A clear understanding of why in measurable terms is key to defining the problem, considering that different values for x will have greater influence on y . (Malsam, 2018)

A cause and effect diagram illustrates potential problem causes. This will encourage focus on the x , not the y . This diagram for CSR testing (figure 11) identifies standard testing to specification in the equipment category which will be measured.

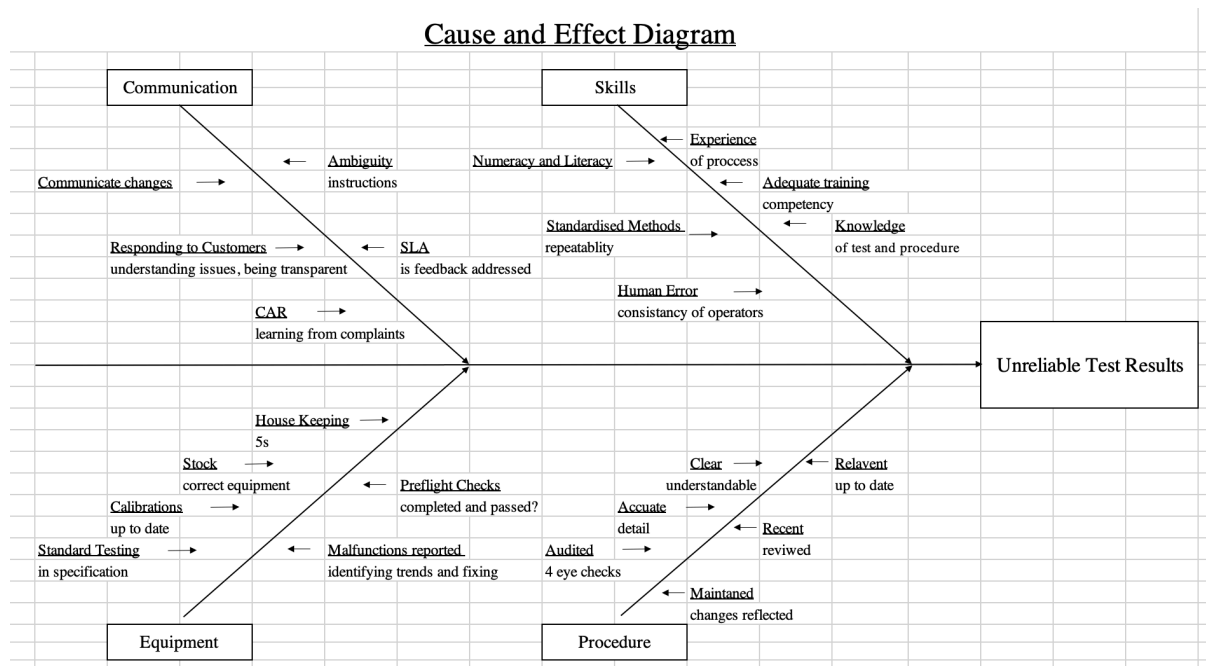


Figure 11 Cause and Effect Diagram

A cause and effect matrix can be constructed from CTQ inputs and outputs, scoring factors based on importance to customer. The matrix (figure 12) identifies the validity of CSR results having the greatest impact on customer satisfaction, accounting for 31%.

Cause and Effect Matrix									
Rating of importance to customer		10	8	7	7	5			
#	KPIV	Quality of coke	Efficiency of coke ovens	Cost of raw materials	Productivity of blast furnace	Predicting blast furnace reactions		Total	% Rank
1	Validity of results	10	10	10	10	10		370	30.96
2	Time to test	1	8	5	10	5		204	17.07
3	Quality of data reporting	3	3	3	3	7		131	10.96
4	Identifying need for retest	3	9	1	10	8		219	18.33
5	Repeatability of results	10	5	5	8	8		271	22.68
Total		27	35	24	41	38		1195	100.00

Figure 12 Cause and Effect Matrix

2.6 Project Charter

A project charter summarises the ‘known and planned’ in a project, the format is reviewed and revised as the project evolves. (Ray, 2017)

Information collected throughout the define stage has been collated into the project charter.

(Note a timeframe is usually established in a project charter, however this investigation is to only define and measure the problems specified, so timeframe has been omitted.) (Pyzdek & Keller, 2012)

Project Charter	
Project Title	Increasing the repeatability of CSR test data in the raw materials lab
Business Case	Invalid test results causes production delays and hinders the prediction of assurance charge, adversely effecting the cost and quality of iron
Project Goal Statement	To tighten the standard test tolerances to identify drift early and increase test accuracy
Customers	Coke oven and blast furnace departments
Critical to Quality Parameter	Delivery of accurate results within the agreed timeframe
Project Boundaries	From time of sample collection at coke ovens to the reporting of the test data

Figure 13 Project Charter

3 Measurement Stage

Measurement stage, determines appropriate techniques for performance data collection in response to the problem, sufficient datasets are collected for problem analysis. (D.P. Deshpande, 2006)

3.1 Identifying Measurement and Variation

In conducting effective process measures, different data type characteristics and their respective variation sources must be considered before selecting the most relevant method.

To measure CSR machine reliability and repeatability, data outputs are measured; this indicates if customer expectations are met. Through these measurements, sources of variation can be isolated, identifying improvement areas.

Variation occurs continuously during this process, through human error, testing material and machine inconsistencies; causing customer dissatisfaction and financial loss. Six sigma aims to reduce variation and meet CTQ's, for this, the variation source must be understood.

3.2 Determining Data Types

A comparison exercise (table 3) is executed prior to selecting a data type.

Variable data is collected allowing continuous measurement, recognising broader magnitudes of the problem.

Data Type	Description	Advantages	Disadvantages	Relevance to Problem
Discrete	Data can only take certain values	• Ideal for failure analysis • Suitable for anything counted	• No continuous measurement	Not useful for measuring data on a continuous scale
Qualitative	Cannot be expressed as numbers	• Good for anything with numerical data (e.g. colour)	• Difficult to identify trends • No magnitude can be measured	Cannot be used for numerical data
Attribute	Data categorised and then counted	• Used to create control charts • Easy to read	• Answers are limited to a specific value (e.g. pass or fail) • No scale is determined to show trends or outliers	Cannot be used for raw numerical data
Variable	Anything that can be measured on a continuous basis	• Helpful to control processes and monitor change	• Can be difficult to visualise without graphs	Ideal to represent data on a continuous scale

Table 3 A comparison of data types (Donges, 2018)

3.3 Developing a Data Collection Plan

A data collection plan organises collection activities, minimising mistakes to ensure successful problem analysis. While developing a data collection plan, the following considerations lead to these decisions (table 4). (Phillips & Stawarski, 2008)

Consideration	Decision
What needs to be known?	CSR machine capability and how testing works.
Potential sources of variation?	Human error (if more than one person collects data). Machine variation and expected variation of destructive test samples.
How much data over what time periods need to be collected?	Six weeks of new data will be collected, note historical data will also be collected for the previous six weeks, totalling twelve weeks to collate a sufficient amount.
How will the measurement system be tested?	External services of gas flow and temperature on the machine will verify that the kit is fit for use.
Are safe working practices (SWP) correct and up to date?	Prior to starting the investigation all SWP's will be reviewed and amended if required.
How will data be displayed?	Raw data will be displayed using normal distribution curves to visualise trends, standard deviations and skewed data.
Where errors in data may occur?	Identified anomalies will be excluded from all further calculations to eliminate skewed data.

Table 4 Considerations about creating data collection plan.

Outcomes of these decisions created a basis for the data collection plan for this investigation in table 5.

Data Collection Plan	
What?	The CSR daily standard test data will be collected.
Why?	To measure the consistency of the machine and the repeatability of the results.
Who?	The area lead technician (Briony Morgan) will be responsible for data collection.
How?	The daily test data will be recorded and saved on a controlled document spreadsheet.
When?	The data will be collected each morning, immediately after testing each day.
Where?	In the raw materials testing laboratory with the CSR testing kit.

Table 5 Data Collection Plan.

Data collection tools accommodate sampling and mitigate errors; automatic email reminders sent to the individuals act as a reminder to collect the data. The raw data is recorded on formatted excel spreadsheets, flagging red any missing data fields will prompt the user to enter all relevant criteria. Daily check sheets are authorised, ensuring no days are missed.

It's not economically feasible to test larger volumes of coke so sampling processes are determined.

For effective sampling, both cost and time must be considered. Both 200g test samples must be representative of thousands of tonnes of coke, so holistic sampling is essential. In this process, systematic sampling methods are used, for every 12 hours of production, 1.4kg of coke is sampled. Samples are split and mixed thoroughly before testing.

A visual of the physical sampling plan (figure 14), explains how specimens are mixed to produce multiple representative samples.

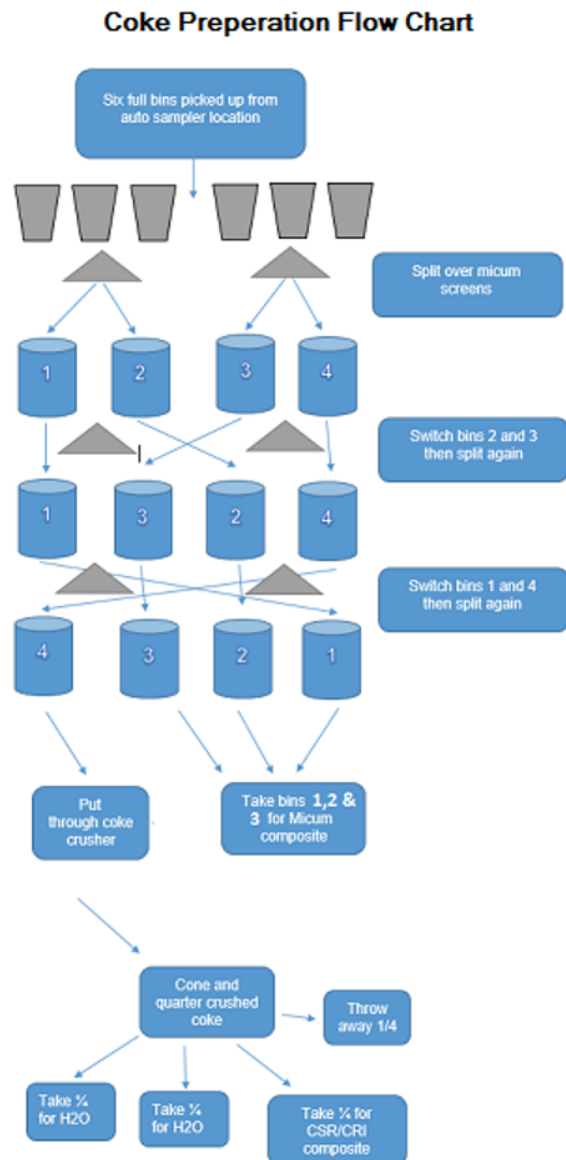


Figure 14 Coke Preparation Flow Chart

The final data collection plan (table 6) will produce sound results through eliminating bias to produce required data via equitable testing.

Project	CSR Machine Validation						
Who	What				When	Where	How
Responsible	Operational Definition	Data Type	Sample Size	Unit of Measurement	Data Time	Location	Collection Method
Technician	Daily Technician	Continuous	400g halved between two tests	Percentage of original weight	21/08/20 - 13/11/20	Raw Materials Laboratory	Input Raw Data Into Excel

Table 6 Data Collection Plan

3.4 Performing Measurement System Analysis (MSA)

MSAs identify variation sources from processes and equipment, improving confidence in results. MSA findings measure system capability and stability, quantifying the magnitude of error and indicating if measurement units are small enough to reflect variation, detecting specific improvements. (Frank Rossi, 2016)

The gage R&R definition method determines measurement system repeatability. To isolate the study to test inherent variability of the measuring system, the same setup will be used by the same operator, replicating environmental conditions to identify where variation occurs for repeated, same sample testing (figure 15).

To calculate the total variation, an additional reproducible MSA would be conducted, identifying variation caused by the measurer (but for the purpose of this investigation, only the system is being investigated).

SP-UK	Measurement Capability Procedure 1A Gauge Capability - Standard																																																														
Measuring Equipment:		Characteristic:																																																													
Gauge Location:	Raw Materials Laboratory	Measured Part:	CSR Teting Rig																																																												
Gauge Description:		Drawing No.:																																																													
Gauge Number:		Characteristic:																																																													
Gauge Resolution:	0.1	Nominal value:	68.600																																																												
		Total Tolerance:	26.610 % Total Tolerance Unit																																																												
Measurement Procedure:																																																															
n= 50 Table values in: 0 Deviation from: <table border="1" style="width: 100%; text-align: center; border-collapse: collapse; font-size: 0.8em;"> <tr> <th>1 - 5</th><th>6 - 10</th><th>11 - 15</th><th>16 - 20</th><th>21 - 25</th><th>26 - 30</th><th>31 - 35</th><th>36 - 40</th><th>41 - 45</th><th>46 - 50</th></tr> <tr><td>71.500</td><td>68.900</td><td>68.800</td><td>71.500</td><td>68.400</td><td>67.700</td><td>64.900</td><td>70.400</td><td>69.200</td><td>67.600</td></tr> <tr><td>69.800</td><td>70.100</td><td>68.900</td><td>71.200</td><td>70.500</td><td>69.100</td><td>70.700</td><td>70.600</td><td>68.900</td><td>65.800</td></tr> <tr><td>67.100</td><td>70.500</td><td>68.900</td><td>69.500</td><td>71.000</td><td>67.500</td><td>69.000</td><td>69.600</td><td>65.200</td><td>69.900</td></tr> <tr><td>68.800</td><td>68.000</td><td>71.600</td><td>70.400</td><td>68.800</td><td>68.700</td><td>68.700</td><td>69.200</td><td>68.200</td><td>68.200</td></tr> <tr><td>72.700</td><td>71.200</td><td>70.200</td><td>70.500</td><td>69.200</td><td>66.100</td><td>68.400</td><td>68.300</td><td>67.400</td><td>68.900</td></tr> </table>				1 - 5	6 - 10	11 - 15	16 - 20	21 - 25	26 - 30	31 - 35	36 - 40	41 - 45	46 - 50	71.500	68.900	68.800	71.500	68.400	67.700	64.900	70.400	69.200	67.600	69.800	70.100	68.900	71.200	70.500	69.100	70.700	70.600	68.900	65.800	67.100	70.500	68.900	69.500	71.000	67.500	69.000	69.600	65.200	69.900	68.800	68.000	71.600	70.400	68.800	68.700	68.700	69.200	68.200	68.200	72.700	71.200	70.200	70.500	69.200	66.100	68.400	68.300	67.400	68.900
1 - 5	6 - 10	11 - 15	16 - 20	21 - 25	26 - 30	31 - 35	36 - 40	41 - 45	46 - 50																																																						
71.500	68.900	68.800	71.500	68.400	67.700	64.900	70.400	69.200	67.600																																																						
69.800	70.100	68.900	71.200	70.500	69.100	70.700	70.600	68.900	65.800																																																						
67.100	70.500	68.900	69.500	71.000	67.500	69.000	69.600	65.200	69.900																																																						
68.800	68.000	71.600	70.400	68.800	68.700	68.700	69.200	68.200	68.200																																																						
72.700	71.200	70.200	70.500	69.200	66.100	68.400	68.300	67.400	68.900																																																						
Ref. Value $x_m = 68.600 \%$ Mean $\bar{x} = 69.124 \%$ Standard Deviation $s = 1.6452 \%$																																																															
Resolution $\leq$ 10% of Tolerance? ☒ Yes ☐ No																																																															
Bias: $ \bar{x} - x_m = 0.524 \%$																																																															
Capability Indices: $C_p = \frac{0.2 \cdot T}{6 \cdot s} = 0.54$ $C_{pk} = \frac{0.1 \cdot T - \bar{x} - x_m }{3 \cdot s} = 0.43$																																																															
Cg $\geq$ 1.33 and Cgk $\geq$ 1.33 ☐ Yes ☒ No																																																															

Figure 15 MSA study

3.5 Collecting Data and Assessing Capabilities

Data collection is an accumulation of information to calculate process capabilities (baseline) to identify problem cause. Too little data collected may be insufficient for problem analysis, too much data could make analysis overly complicated.

To ensure collection of optimum data, capability assessments are essential; operator competency evidence is required, frequent auditing should be embedded. Clear reporting systems are used to easily identify anomalous results. Data collected in quick succession will identify a shift change in data but not long-term drift which occurs slowly over time.

Analysing capabilities establish how well processes meet CTQ's, determining natural variation and creating a reference point for improvement (table 7).

Nominal Value	Specification	Lower Tolerance	Upper Tolerance	Data Distribution Type
68.6	BS ISO 18894:2018	65.939	71.261	Normal Distribution curve

Table 7 Summary of Capability Analysis

The raw data (table 8) is collated and presented using a normal distribution curve (figure 16) as part of the capability analysis.

Date	CSR Value	Normal Dist.
21/08/2020	57.4	0.01253582
22/08/2020	60.5	0.03902493
23/08/2020	59.3	0.02662496
24/08/2020	55.4	0.00466397
25/08/2020	61.2	0.04717432
26/08/2020	57.2	0.01145877
27/08/2020	57.5	0.01310186
28/08/2020	58.1	0.01689799
29/08/2020	58.2	0.01759904
30/08/2020	60.5	0.03902493
31/08/2020	59.1	0.02480622
01/09/2020	60.1	0.0346322
02/09/2020	59.2	0.02570595
03/09/2020	56.7	0.00907372
04/09/2020	60.1	0.0346322
05/09/2020	55.8	0.00577581
06/09/2020	63.2	0.07081968
07/09/2020	57.8	0.01491301

Date	CSR Value	Normal Dist.
06/10/2020	68.2	0.08122155
07/10/2020	69.9	0.06393262
08/10/2020	65.8	0.08894825
09/10/2020	67.6	0.08537152
10/10/2020	67.4	0.08645347
11/10/2020	68.2	0.08122155
12/10/2020	67.1	0.08777102
13/10/2020	65.2	0.08697183
14/10/2020	68.9	0.07490329
15/10/2020	69.2	0.07180538
16/10/2020	68.3	0.08040834
17/10/2020	69.2	0.07180538
18/10/2020	65.2	0.08697183
19/10/2020	69.6	0.06739779
20/10/2020	70.6	0.05553964
21/10/2020	70.4	0.0579637
22/10/2020	68.4	0.07956332
23/10/2020	68.7	0.07684929

08/09/2020	59	0.02392595
09/09/2020	60	0.03357139
10/09/2020	65.3	0.08740781
11/09/2020	69.8	0.06510009
12/09/2020	71.5	0.04470136
13/09/2020	68	0.08274798
14/09/2020	68.1	0.0820018
15/09/2020	68.3	0.08040834
16/09/2020	65.3	0.08740781
17/09/2020	67.7	0.08477176
18/09/2020	68.4	0.07956332
19/09/2020	66.1	0.08934556
20/09/2020	69.4	0.06963658
21/09/2020	67.6	0.08537152
22/09/2020	68.6	0.07778257
23/09/2020	69.3	0.07073042
24/09/2020	67.1	0.08777102
25/09/2020	69.1	0.07286009
26/09/2020	67.3	0.08693408
27/09/2020	67.1	0.08777102
28/09/2020	65.7	0.08872706
29/09/2020	69.5	0.06852524
30/09/2020	68.3	0.08040834
01/10/2020	69.6	0.06739779
02/10/2020	67	0.08812611
03/10/2020	69.5	0.06852524
04/10/2020	68.8	0.0758891
05/10/2020	68.9	0.07490329

Table 8 Raw data

Mean	66.2
Standard deviation	4.463
Target	68.6
USL	71.261
LCL	65.939

Table 9 Table of calculations

24/10/2020	69	0.07389317
25/10/2020	70.7	0.05432497
26/10/2020	64.9	0.08541918
27/10/2020	66.1	0.08934556
28/10/2020	68.7	0.07684929
29/10/2020	67.5	0.08593236
30/10/2020	69.1	0.07286009
31/10/2020	67.7	0.08477176
01/11/2020	69.2	0.07180538
02/11/2020	68.8	0.0758891
03/11/2020	71	0.05068511
04/11/2020	70.5	0.05675297
05/11/2020	68.4	0.07956332
06/11/2020	70.5	0.05675297
07/11/2020	70.4	0.0579637
08/11/2020	69.5	0.06852524
09/11/2020	71.2	0.04827372
10/11/2020	71.5	0.04470136
11/11/2020	70.2	0.06037217
12/11/2020	71.6	0.04352659
13/11/2020	68.9	0.07490329

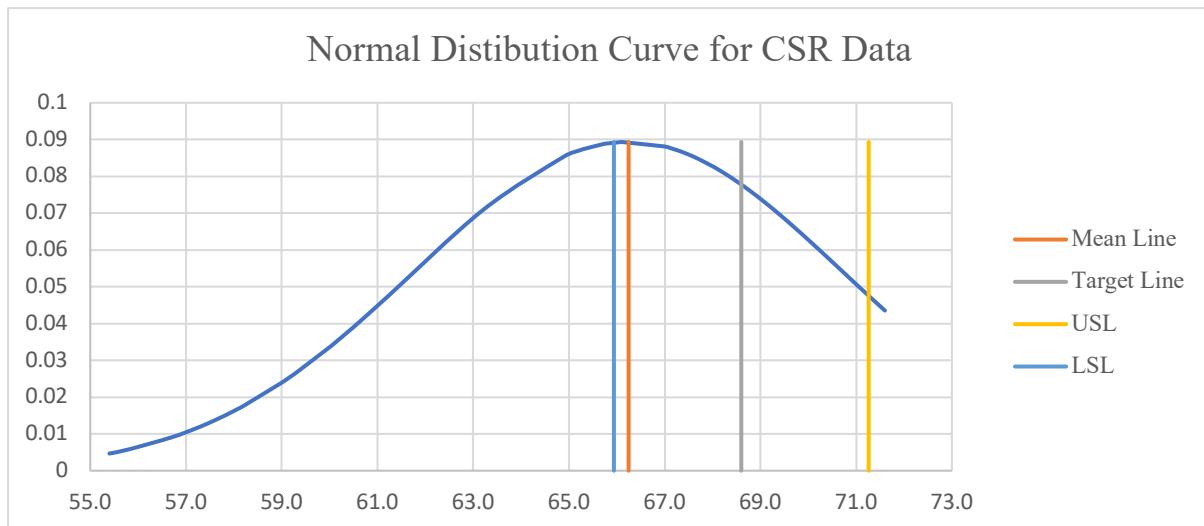


Figure 16 Normal distribution for CSR data

Ideally, the target and mean line are consistent with each other, figure 16 shows a significant difference, where mean is lower than the target.

There is significant deviation of results represented by a shallow curve.

Standard deviations are high relative to the data pool.

A large amount of results sit below the LSL, indicating high numbers of failure.

A process capability (C_p) of 0.2 was calculated, highlighting that the process is severely incapable of meeting CTQs.

3.6 FMEA (Failure mode and effects analysis) & Risk Evaluations

An FMEA documents potential failures in the process, identifying actions to mitigate risks; documenting current controls, prioritising actions and recording historical improvements (table 10). (Patel & Parsana, 2014)

Process Flow Step No.	Process Function / Requirement	Potential Failure Mode	Potential Effect(s) of Failure	SEVERITY	OCCURRENCE	DETECTION	Class	Criticality	Risk Priority Number (RPN)
1	CSR Testing	Non representative sample (not mixed correctly)	Inaccurate data provided to production unit, resulting in final product failing to meet specification.	7	4	9	Manufacturing and Customer	28	252
		Results fail to meet repeatability criteria.	Retests required, resulting in economic loss through yield losses, man hours.	5	7	1	Economic	35	35
		Incorrect reporting of results.	Potential effects include significant loss in material through scrapping unidentified product, alternatively the product can be used blind, compromising output quality (should the results not be retrievable)	10	2	5	Manufacturing and Customer	20	100

Table 10 FMEA Tool and Risk Evaluation

Evaluating risk identifies the highest potential failure, calculating their severity and occurrence. Using the FMEA tool criticality was calculated to determine that failure to meet repeatability is the highest risk. When taking into account the chance of detection, incorrect reporting of results was identified as the highest risk.

4 Conclusions

4.1 Findings

Through defining and measuring CSR testing using DMAIC methodologies, numerous shortfalls have been highlighted via various tools and techniques. Prioritisation of these shortfalls established the greatest contribution to customer dissatisfaction. Through process mapping and root cause analysis, sources of error are identified to propose solutions. An MSA study supports that machinery is not effectively meeting customer expectations, in addition to a skewed distribution with an unacceptable Cp value of 0.2. The FMEA exposes that inconsistent data poses the highest risk to process quality, also highlighting that detection methods can be improved to mitigate risks. These improvements should be addressed first as they have the biggest impact on CTQs.

4.2 Error

The following modes of error are identified:

- In the final problem statement, no quantifiable figure to state the variation amount, only through further measurements is the magnitude of variation identified. The statement could be considered anecdotal as investigations are based on customer feedback.
- Due to the nature of destructive testing, it's impossible to test identical specimens, introducing error.
- For economical and health and safety purposes, 1.4kg samples sizes are collected. Larger sample sizes will increase homogeneity, being more representative, this small sample will produce inconsistencies.

4.3 Recommendations

Upon completion of the DMAIC method, it's good practice to reuse the tool, this will identify missed or new issues to continuously improve the service. (Dale, 2003)

Throughout measurement stages, only internal standards were used to determine process capability which has various sources of error, going forward using an accredited proficiency scheme will provide more reliable and accurate analysis.

A more thorough analysis requires collection of larger pools of data, over longer timeframes.

5 Works Cited

- Attard, J., 2014. *Why do I need a SIPOC?*. [Online]
Available at: <https://www.100pceffective.com/blog/need-sipoc-process-map/>
[Accessed 6th November 2020].
- British Standards Institution, 2018. *Coke-Determination of coke reactivity index (CRI) and coke strength after reaction (CSR)*. 2nd ed. Geneva: BSI Standards Publication.
- D.P. Deshpande, S. H. S. B. A. R. A. C. A. K., 2006. Process improvement at Tata Steel using the ASPIRE DMAIC approach (Chapter 3). In: D. A. K. M. R. B. Dr. Jiju Antony, ed. *World Class Applications of Six Sigma*. Oxford: Elsevier, pp. 45-61.
- Dale, B. G., 2003. *Managing Quality*. 4th Edition ed. s.l.:Blackwell.
- Donges, N., 2018. *Data Types in Statistics*. [Online]
Available at: <https://towardsdatascience.com/data-types-in-statistics-347e152e8bee>
[Accessed 12th November 2020].
- Frank Rossi, V. M., 2016. Chapter 5 - Measurement Systems Analysis (MSA). In: *Statistics for Food Scientists*. Illinois: Academic Press, pp. 31-52.
- Gray, R. J., 1989. *Introduction to Carbon Science, Chapter 9 - Coal to Coke Conversion*. 1st ed. Monroeville: Butterworth-Heinemann.
- Jeroen de Mast, J. L., 2012. *An analysis of the Six Sigma DMAIC method from the perspective of problem solving*. 2nd ed. Amsterdam: Elsevier.
- M.A. Díez, R. A. C. B., 2001. *Coal for metallurgical coke production: predictions of coke quality and future requirements for cokemaking*. 1st ed. Ovideo: Elsevier.
- M.T.Pereira, M. I. L. J. F. A., 2020. *Using Six Sigma to analyse Customer Satisfaction at the product design and development stage*. 1st ed. Porto: Elsevier.
- Malsam, W., 2018. *What Does $Y=f(x)$ Mean? How to Use This Powerful Six Sigma Formula*. [Online]
Available at: <https://www.projectmanager.com/blog/yfx-six-sigma-formula>
[Accessed 10th November 2020].
- Michael Hein, M. K., 2012. *Air Pollution, Chapter - Environmental Control and Emission Reduction for Coking Plants*. 2nd ed. Rijeka: IntechOpen.
- Monika Smętkowska, B. M., 2018. *Using Six Sigma DMAIC to Improve the Quality of the Production Process: A Case Study*. 1st ed. Poznan: Elsevier.
- Patel, M. T. & Parsana, T. S., 2014. *A Case Study: A Process FMEA Tool to Enhance Quality and Efficiency of Manufacturing Industry*. [Online]
Available at:
https://www.researchgate.net/publication/287694384_A_Case_Study_A_Process_FMEA_Tool_to_Enhance_Quality_and_Efficiency_of_Manufacturing_Industry
[Accessed 20 November 2020].
- Phillips, P. P. & Stawarski, C. A., 2008. *Data Collection: Planning for and Collecting All Types of Data*. s.l.:Pfeiffer.
- Prasher, A., 2014. Process improvement in farm equipment sector (FES): a case on Six Sigma adoption. In: *International Journal of Lean Six Sigma*. s.l.:Emerald Group Publishing Limited, pp. 62-88.
- Product Plan, 2020. *Kano Model*. [Online]
Available at: <https://www.productplan.com/glossary/kano-model/>
[Accessed 9th November 2020].
- Pyzdek, T. & Keller, P., 2012. *Six Sigma Handbook A Complete Guide for Greenbelts, Blackbelts and Managers at All Levels*. 3rd ed. New York: McGraw Hill.
- R.S.Barot, J. P. B. S. B. R. H. S. Y. P., 2020. *Lean six sigma feasibility and implementation aspect in cast iron foundry*. 3rd ed. Vitthal Udyog Nagar: Elsevier.

Ray, S., 2017. *A Quick Guide to Project Charters*. [Online]

Available at: <https://www.projectmanager.com/blog/project-charter>

[Accessed 10th November 2020].

Xing, X., 2019. *Fuel Processing Technology, Effects of coal interactions during cokemaking on coke properties under simulated blast furnace conditions*. 1st ed. Sydney: Elsevier.