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Key Words

Machine Learning; Fuzzy Logic; Artificial Intelligence; Coke Plant; CSR; CET; CDQ

Abbreviations

CDQ: Coke Dry Quenching; CSR: Coke Strength after Reaction; CP: Coke Plant; BF: Blast Furnace; CET: Coke End Temperature

Review Article

Digital Transformation of Coke Oven Batteries: A Path to Efficiency

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Abstract

Digitalization improves the production, quality, health & safety. This paper is about the digital models developed and integrated into Coke Oven Scheduling & Heating Monitoring System. Explored first principal methods, conditional based algorithms, various machine learning and artificial intelligence techniques, namely XGBoost, Random Forest, Decision tree & GLM to build predictive, prescriptive & descriptive models. Descriptive analysis & exploratory data analysis have been done to get insights from the data. Machine learning models were tuned for their optimum hyperparameters using grid search algorithms iteratively. Models with high accuracy have been deployed. Good operating zone/ranges have been defined for controllable parameters using Partial dependency plots.

Introduction

Coke is one of the most important raw materials fed into the blast furnace. It has tremendous effect on blast furnace operation and hot metal quality. Metallurgical coke, a vital component in iron and steel production, is primarily used in blast furnaces for reducing iron ore to iron, accounting for over 90% of coke consumption. The remaining balance is utilized as foundry coke, employing different blends of coking coals, longer coking times, and lower temperatures, in foundries for metal melting and casting [1-7]. Coke significantly contributes to the cost of hot metal production, making the cost-effective production of high-quality coke crucial for the competitiveness of the iron industry. The majority of global coke production relies on by-product coke oven batteries, often integrated with iron and steel production facilities. With intense competition and fluctuating coal bases, reducing coke production costs is a key challenge for the iron and steel industry [8-11]. Automation, Control, and Measurement System of Coke Oven Plants: Optimizing Metallurgical Coke Production

Metallurgical coke is essential for iron and steel production, mainly used in blast furnaces for reducing iron ore. With over 90% of coke dedicated to this process, cost-effective and high-quality coke production is crucial for the industry's competitiveness. Most coke is produced using by-product coke oven batteries, and reducing production costs is a significant challenge. The Coke Oven Plant (COP) employs a complex process of thermal distillation in groups of ovens called batteries. These ovens are carefully constructed with shared walls made of high-quality silica and refractory bricks. The coking process, occurring over 15-18 hours, involves heating coal to temperatures between 900 °C and 1,100 °C. This process is carefully controlled to ensure uniform heating and the production of blast furnace coke [12-15].

The cyclic operation of each oven contributes to a continuous flow of raw coke oven gas. Coking times can be extended up to 24 hours during low demand periods [16,17]. The coking process is intricate, with various variables and parameters influencing the outcome. COP is crucial as it produces coke and coke oven gas, which are essential for iron and steel production. The quality and output of these products directly impact the stability of iron and steel operations. To optimize efficiency, COP requires an automation, control, and measurement system. This system is designed with a modular structure, offering flexibility to meet specific plant requirements. It helps improve productivity, stabilize coke oven operations, enhance coke quality, reduce emissions, extend battery life, and facilitate data analysis and reporting [18,19].

The automation, control, and measurement system is structured across classic levels, from Level 0 (field level) to Level 3 (management level), providing a user-friendly tool to enhance the overall performance and stability of the coke oven plant [20-23]. High-quality coke should be able to support a smooth descent of the blast furnace burden with as little degradation as possible while providing the lowest number of impurities, highest thermal energy, highest metal reduction, and optimum permeability for the flow of gaseous and molten products. High quality of coke to a blast furnace will result in lower coke rate, higher productivity, and lower hot metal cost.

Description of Coke Plant Process

The Coke Plant Battery consist of set of ovens. Each oven scheduling implies scheduling of oven Pushing/Charging. Four machines are required to operate in one battery. These machines will work based on oven scheduling, followed by cross battery interlocking. The coke making process involves the carbonization of coal to high temperatures (1100+ ℃) in an oxygen-deficient atmosphere to concentrate the carbon.

Functional architecture of coke oven automation

The "Computerized Combustion Control System" for Coke Oven Battery 1 and 2, Tata Steel aims towards high regularity in operations, consistency in coke quality and reduction in human co-ordination needed amongst different operating machines involved in battery operations. Heating control results in energy savings and improved battery life. The system consists of the following functions. Overall functional interconnectivity is shown in Figure 1.

a. Pushing/Charging Schedule for Ovens
b. Machine Group
c. Heat Control
d. Process Data Acquisition, analysis and Compression
e. HMI (UI)
f. Reports and Graphs

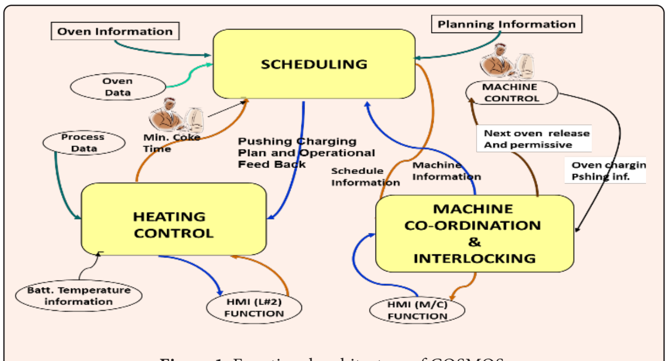


Figure 1: Functional architecture of COSMOS.

Dynamic oven schedule

Scheduling of battery: The scheduling process generates the sequence & timing of operation events, i.e., pushing and charging based on desired/setpoint coking time. Based on the operating events & maintenance inputs from the operator, the schedule is generated for a battery. Under scheduling, there are various sub-tasks, which provide preparing plans for each shift and also observe the status of all the ovens of battery as shown in Figures 2,3. Default Configuration is:

Oven Offset: 5

Series Offset: 2

The functionalities for failure mode operation are

a. Sequence/Out of sequence of an oven.

b. Simulating manual pushing/charging completion.

c. Rescheduling of an oven.

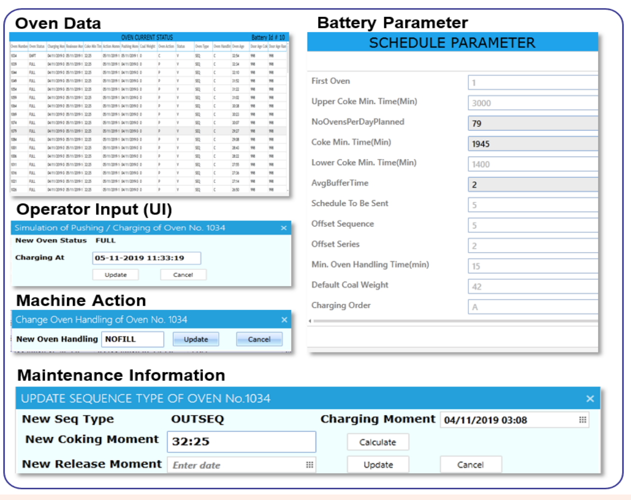


Figure 2: COSMOS schedule & failure mode HMI.

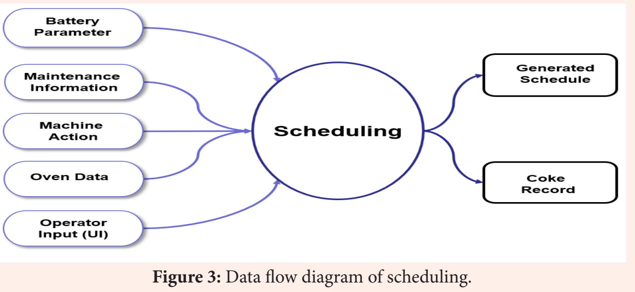


Figure 3: Data flow diagram of scheduling.

Scheduling based on gooseneck temperature to predict coking time: Each oven scheduling implies scheduling of oven Pushing/Charging event. The total time taken to complete one cycle of an oven is coking time, i.e., (from charging time of coal to pushing time of coke). Usually, the target coking time for all ovens is given by the operator in COSMOS based on the target number of ovens to be pushed. But the actual coking time may be different depending upon various operating conditions. By definition, coking time is the time taken by the oven to reach the carbonization completion temperature (the temperature at which volatile matter of coal is completely burnt out). A model has been developed to predict actual carbonization time based on the temperature trend measured by gooseneck thermocouple (see Figure 4), which is mounted at the top of each oven.

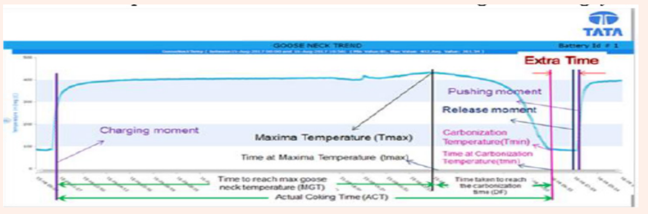
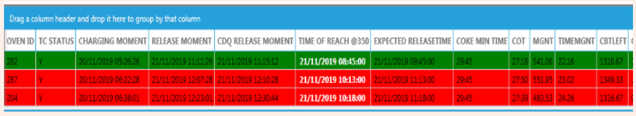


Figure 4: Gooseneck temperature characteristics of an oven.

It shows the next three ovens which is going to be pushed in a schedule as shown in Figure 5.

a. The green colour indicates carbonization time is completed.

b. The red colour indicates carbonization time is not achieved.



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OVEN ID	TC STATUS	CHARGING MOMENT	RELEASE MOMENT	CDQ RELEASE MOMENT	TIME OF REACH @350	EXPECTED RELEASETIME	COKE MIN TIME	COT	MGNT	TIMEMGNT	CBTLEFT
282	Y	20/11/2019 05:26:26	21/11/2019 11:11:26	21/11/2019 11:15:12	21/11/2019 08:45:00	21/11/2019 09:45:00	29:45	27:18	541.06	22.16	1310.67
287	Y	20/11/2019 06:22:28	21/11/2019 12:07:28	21/11/2019 12:10:28	21/11/2019 10:13:00	21/11/2019 11:13:00	29:45	27:50	551.95	23.02	1349.33
204	Y	20/11/2019 06:38:01	21/11/2019 12:23:01	21/11/2019 12:30:44	21/11/2019 10:18:00	21/11/2019 11:18:00	29:45	27:39	483.53	24.26	1316.67

Figure 5: Visibility of top three ovens release moment based on gooseneck temperature.

Maximum carbonization is detected from gooseneck graph as shown in Figure 6. Data analysis between Coke End Temperature (CET) & Coke Strength After Reduction (CSR) suggest that the CSR will always more than 65 if CET is more than 1004 as shown in Figure 7.

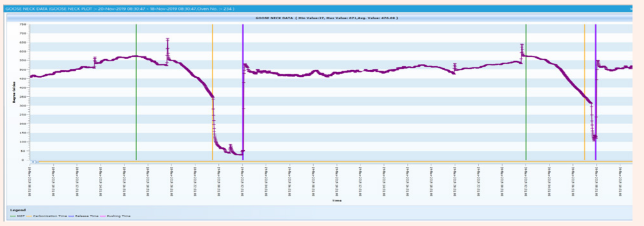


Figure 6: Visibility of time taken to reach maximum temperature and carbonization event.

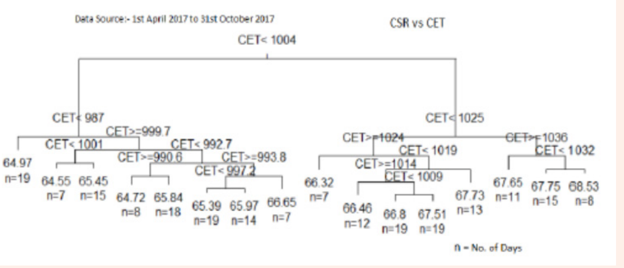


Figure 7: Decision tree between CET & CSR.

Scheduling of coke dry quenching: In case of one coke dry quenching system is available, which has to be shared by two batteries, and this is located centrally between both batteries. This common scheduling system will maximize common CDQ usage. This common schedule is generated in COSMOS, which changes dynamically depending on different levers like travel distance, traveling time, crane availability, and battery delay as shown in Figure 8.

Benefits:

a. Minimizes the loco waiting time
b. Optimizes CDQ Usage
c. Increases the battery production

Drag a column header and drop it here to group by that column

OVEN ID	CHARGING MOMENT	RELEASE MOMENT	CDQ RELEASE MOMENT
131	20/11/2019 04:48:13	21/11/2019 10:48:13	21/11/2019 10:56:13
136	20/11/2019 05:01:09	21/11/2019 11:01:09	21/11/2019 11:09:09
282	20/11/2019 05:26:26	21/11/2019 11:11:26	21/11/2019 11:15:12
141	20/11/2019 05:22:20	21/11/2019 11:22:20	21/11/2019 11:30:20
146	20/11/2019 05:37:40	21/11/2019 11:37:40	21/11/2019 11:45:40

Figure 8: Scheduling of coke dry quenching.

Machine coordination

The following basic functionality of Machine coordination:

a. Grouping set of five specific machines one of each machine-type as the operational machine group working on the battery.
b. Establish the mode of operation for the machine group-Active or Maintenance.
c. Receive and process Pushing and charging related data like Push Current, Charge Current, Oven Wall Temperature, Coke End Temperature etc. from active machine for acted Oven.
d. Communicate battery schedule to the machines, which are part of active group. On every pushing and charging and schedule request.
e. Communicate released oven schedule to the machines, which are part of active group. Oven is said to be released when its min coking time has expired. Until an oven is not pushed and charged, Next release schedule will not be sent.
f. Display the actual position and activated function on the operational machines for level II Operator.
g. Machine Availability (Machine uptime/downtime) and efficiency.
h. For group change, provision will be there for ease of operation.

Based on group, machines will coordinate for activities like Schedule download, Release time for oven, pushing/charging etc. as shown in Figure 9. For creating machine groups, a machine management screen is used. This screen is used for creating machine Groups. Machine groups can be Active or Maintenance. All the Machines which are in usage are kept under the Active group shown in Figure 10. Machine group information will come from PLC. This can be seen in active machine on the screen, one can change the group from level 2 system and send the new machine group information to PLC as shown in Figure 11. Active machines for battery 1 & 2 are shown in Green colour & the machines which are in maintenance are displayed in Red colour. To change the Machine Group, one have to drag the machine from one group to another, it will ask for confirmation which can be confirmed to change the Machine Group, followed by click on send to PLC if you want to send the new group to PLC as shown in Figure 12.

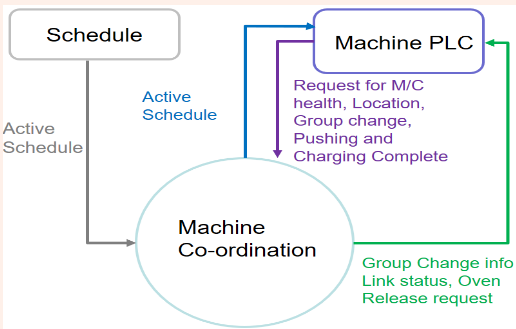


Figure 9: Data flow diagram of machine co-ordination.

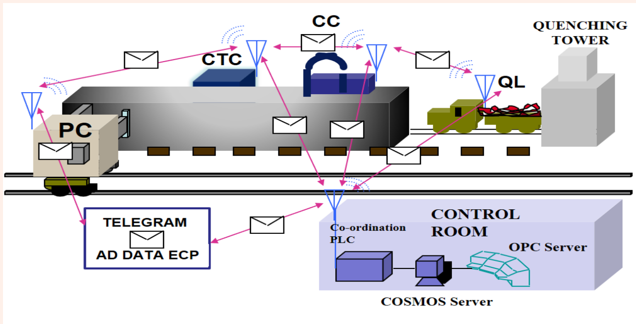


Figure 10: Data flow diagram/Telegram exchange between machine PLC with Control room PLC.

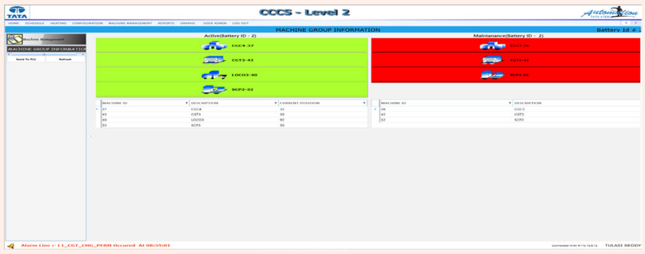


Figure 11: Machine group change.

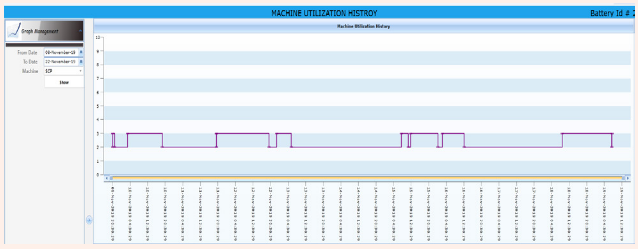


Figure 12: Machine management.

Battery heating control model

During coking cycle, after each 20 minutes, a phenomenon called reversal takes place, when the roles of combustion and exhaust flues are reversed and combustion flue becomes exhaust flue and exhaust flue becomes combustion flue. There is a time at the start of reversal when no fuel to the battery is supplied. This period is called pause time. This model calculates the pause for each reversal. The heating module is based on state of the art closed-loop fuzzy controller using different parameters like average regenerator temperature, coke mass temperature and other various parameters as shown in Figure 13. It controls the gas flow to maintain the regenerator temperature in desired set value by calculating the pause time in a reversal as shown in Figure 14.

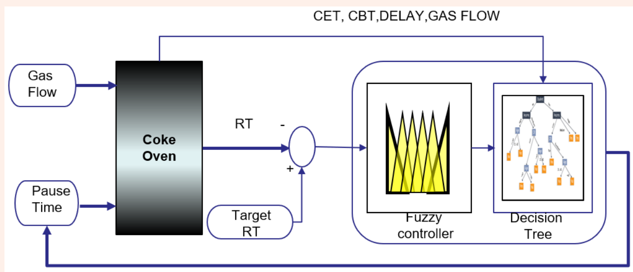


Figure 13: Heat pause model.

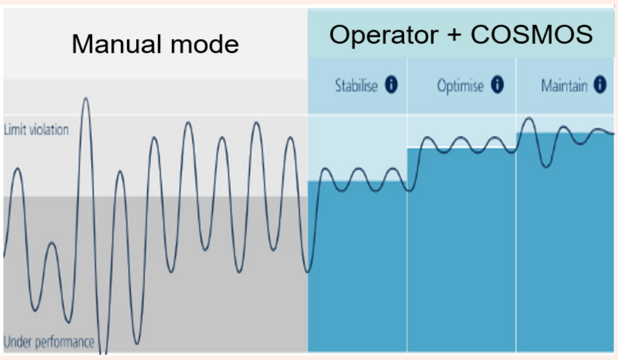


Figure 14: Heat pause model performance.

Smart dashboard

Coke end temperature stratification: Coke end temperature is a significant parameter for coke quality and battery health. COSMOS temperature evaluation model shows the battery health based on the CET. Heat map of Coke end temperature shown in Figure 15.

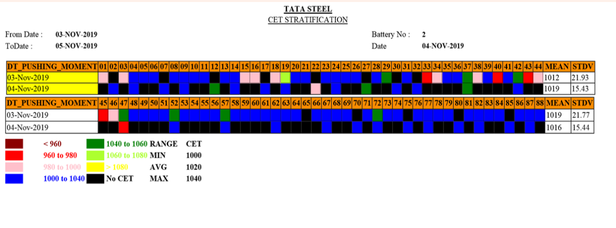


Figure 15: CET stratification.

Oven health based on pusher ram force: This is a battery health monitoring model to improve battery life using machine learning. It gives an early indicator to identify the health of an oven as shown in Figure 16. A visualization system is developed to identify the bad performing oven for preventive maintenance using early indicators. The good range for the early indicator to improve the oven health has been derived by using partial dependency plots from the best-performed machine learning algorithm, keeping production & quality of coke in the acceptable range.

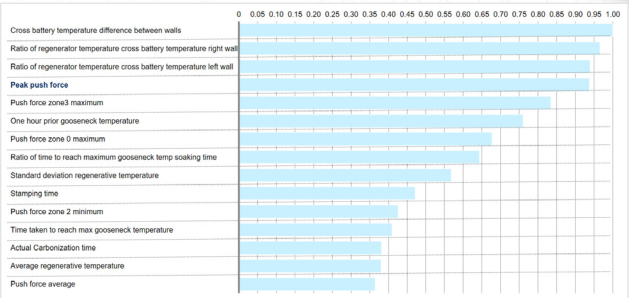


Figure 16: Variable importance plot of battery health model.

Following are the model Outputs:

Visibility of break amps from push force of an oven (see Figure 17).

Visibility of summary of push force.

Visibility of Push force index (Oven healthiness % with respect to push force for last 7 days).

This visualization system acts as a enabler to identify poor performing ovens for prioritized maintenance (see Figure 18). After implementation, good operating zone ovens performance has increased from 41% to 91% as shown Figure 19.

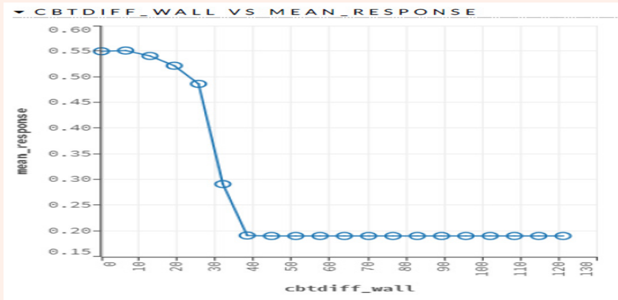


Figure 17: Deducing best ranges using partial dependency plot.

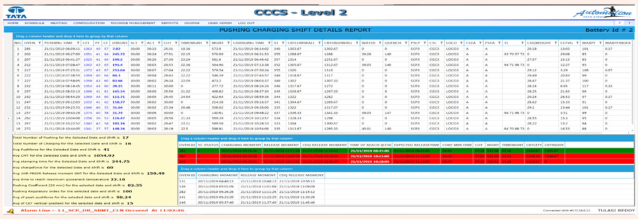


Figure 18: Push force index.

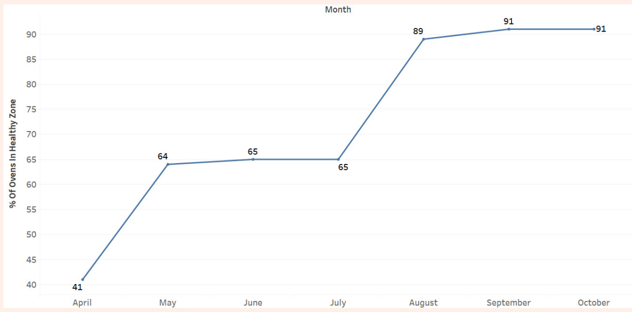


Figure 19: Improvement in oven performance after by Push force model.

Oven maintenance: Using machine learning algorithms, a relationship has been defined for coke end temperature and coke strength after reaction & also deduced a relationship among gooseneck parameters. Oven maintenance dashboard helps to identify the bad performing of ovens based on the time taken to reach maximum gooseneck temperature, coke end temperature & carbonization temperature as shown in Figure 20.

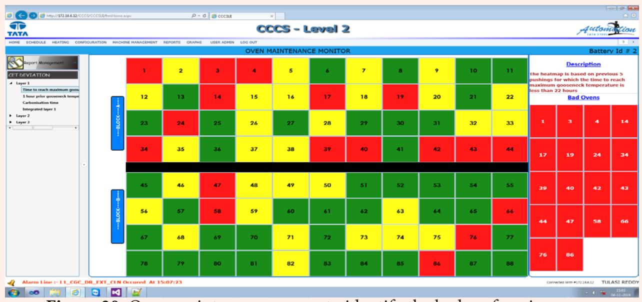


Figure 20: Oven maintenance screen to identify the bad performing ovens.

Coke discharge rate setpoint model for CDQ

It is a supervised coke dry quenching model to improve the CDQ utilization and process safety. It calculates the coke discharge rate setpoint based on battery & CDQ process parameters (see Figure 21) to maintain the chamber level within an acceptable range. This model acts as a closed-loop control model which operates CDQ automatically.

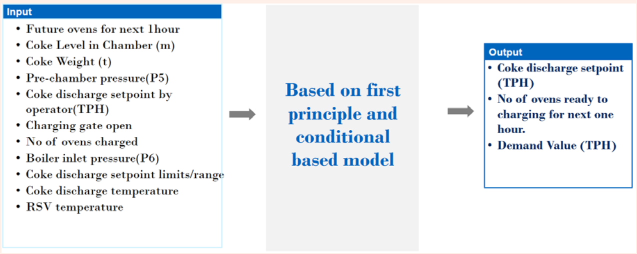


Figure 21: Coke discharge rate model with input & output variables.

Benefits:

a. Maximizes the utilization of CDQ & Boiler Power
b. Increases the life of the chamber
c. Reduces the maintenance of boiler tubes by increasing life
d. Maintains CDQ process parameters within the tolerable ranges like boiler inlet pressure, CO, etc.
e. Reduces the coke moisture content.

Ensure process safety & prevent blast due to gas accumulation leading to pressure build-up inside the chamber.

Auto delay logging system

Delay logging system calculates the delay automatically as shown in Figure 22.

Benefits:

a. Zero error
b. Fully automatic
c. Easy for analysis
d. Ease in operation

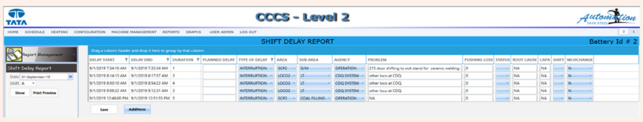
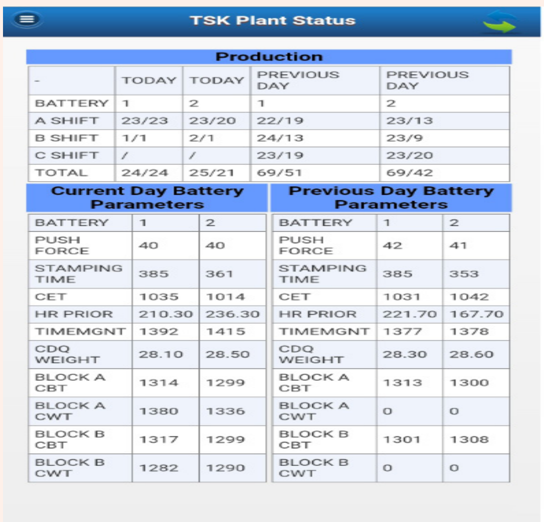


Figure 22: Delay report.

Mobile app for operation

Ease to access mobile app for coke makers. Visibility of both battery CDQ production & process control parameters as shown in Figure 23.


TSK Plant Status

Production

-	TODAY	TODAY	PREVIOUS DAY	PREVIOUS DAY
BATTERY	1	2	1	2
A SHIFT	23/23	23/20	22/19	23/13
B SHIFT	1/1	2/1	24/13	23/9
C SHIFT	/	/	23/19	23/20
TOTAL	24/24	25/21	69/51	69/42

Current Day Battery Parameters			Previous Day Battery Parameters		
BATTERY	1	2	BATTERY	1	2
PUSH FORCE	40	40	PUSH FORCE	42	41
STAMPING TIME	385	361	STAMPING TIME	385	353
CET	1035	1014	CET	1031	1042
HR PRIOR	210.30	236.30	HR PRIOR	221.70	167.70
TIMEMGNT	1392	1415	TIMEMGNT	1377	1378
CDQ WEIGHT	28.10	28.50	CDQ WEIGHT	28.30	28.60
BLOCK A CBT	1314	1299	BLOCK A CBT	1313	1300
BLOCK A CWT	1380	1336	BLOCK A CWT	0	0
BLOCK B CBT	1317	1299	BLOCK B CBT	1301	1308
BLOCK B CWT	1282	1290	BLOCK B CWT	0	0

Figure 23: Mobile application.

Management information system & data historization

The 'Human Machine Interface' (HMI) system is an important tool to access all available information. This gives authorized access to data and functionality to both operators and all other people within the organization, who are involved in the process of coke production. Furthermore, it must allow a user-friendly, clearly organized and efficient view of the current and historical process data as shown in Figure 24.

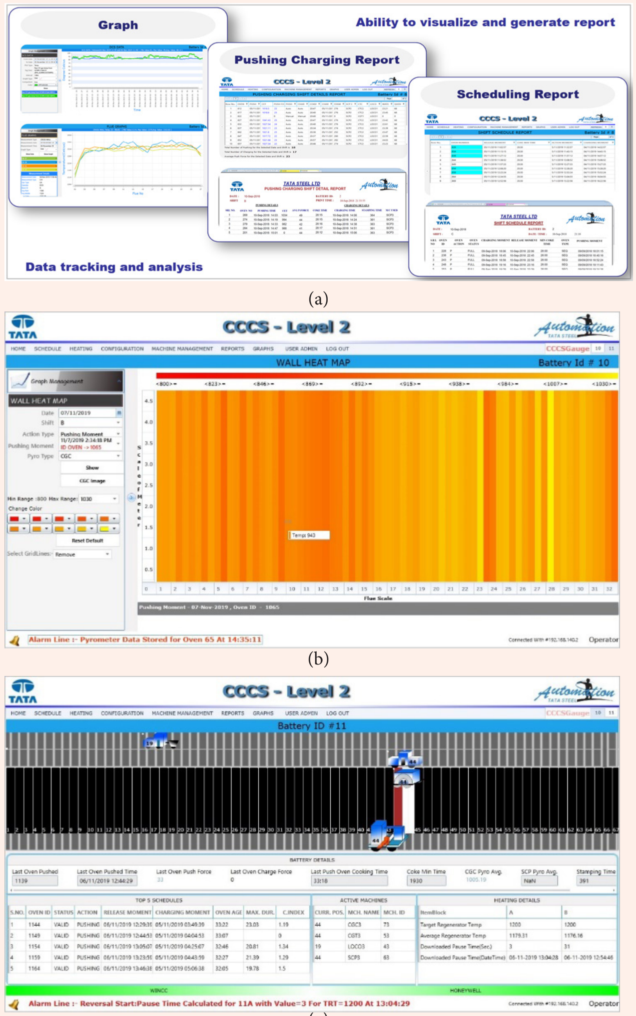


Figure 24: (a), (b) & (c) Reports, graphs & home screen.

Smart barricade

It is an IOT based application which aims to provide access control at work place and monitor person working in hazardous area for limited Period of time only as per specified standard. Earlier manual register was maintained for person entering for work in hazardous area and even an outsider can enter to the hazardous work place which was not traceable as shown in Figure 25.

System Features:

a. IOT based Application, barricade devices are remotely accessed & controlled.
b. Real Time people tracking & access for authorized person only.
c. MIS, Reports & Alerts for person exceedingly more than specified working hours.
d. Barricade works with all Employee/Contractor gate pass.
e. Authentication is done via gate pass section database over cloud.
f. Emergency system available near barricade to escape from area in case of any exigency.

Benefits:

i. Improved safety by providing visibility of person working in hazardous area.

ii. Single application Scalable across various units.

iii. Allow only authorize person to pass through barricade at work place.

iv. Person are now aware and cautious about working hours in hazardous area.

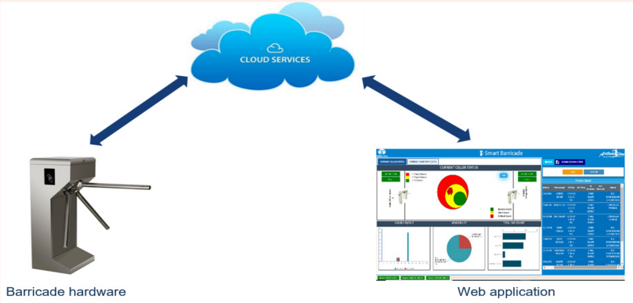


Figure 25: Smart barricade data flow.

Tie rod load visualization system

Anchorage is required to support the battery brick work. The main element of the steel work consists of buck stay on each side of the battery between each oven connected through transverse tie rods running across the battery. Life of battery greatly depends on the condition of anchoring & its performance. Presently no system exists to know the online load variation on oven bracing system due to variation in parameter (change of ambient temp, coal blend, Operating regime change etc). The system get real time load variation of the Tie rods.

A high temperature washer type Load Cell is installed at the Tie rod ends of battery in 2 no. oven. A total 4 number of Loadcells are installed in these two ovens. Signal is directly interfaced with the DCS. An application has been developed to analyze the Load variation of the ovens in normal condition as well as during pushing and charging.

Benefits of the system are:

a. Increasing productivity by reducing the manual load adjustment campaigns. Four cycles of adjustment per battery per year is followed.

b. Improves the process visibility. Help to decide the coal blend by monitoring the maximum swelling load generated by the coal cake on heating wall during carbonization period (see Figure 26).

c. Monitor the load variation on oven bracing due to changing parameters like heavy rain, ambient temperature, Change in thermal regime of the battery, coal cake brakeage etc.

d. Alerts on high push force or charging force in terms of wall pressure. Corrective action can be taken to minimize both forces.

e. Carbonation time of the coal cake can be determined.

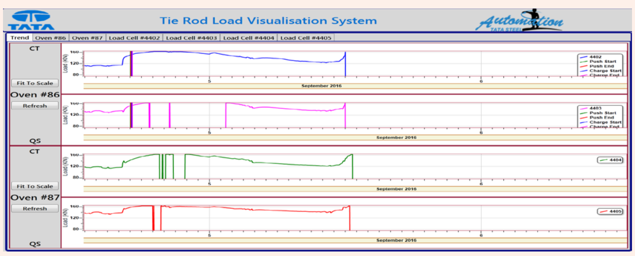


Figure 26: Tie Rod HMI.

Online flue temperature measurement system

Traditionally Flue temperature measurement is being done manually, where people go to the oven top, open the flue cap and manually focus the handheld pyrometer into the flue to measure the temperature. This is being done thrice in a shift depending upon the schedule. Two modes are being followed, Cross battery and the cross oven. This system deals with measuring the temperature of all the flues continuously with a single online pyrometer as shown in Figure 27. A three axis moving head is designed to take the Fiber lens at each probe; it stays there for 2 seconds, gather the temperature data and moves on. This system is running continuously 24X7. Three servo motors are being used to control the movement of the head on the probe platform. One S7 1200 PLC is controlling the entire movement. The Analog input port of the PLC is taking the pyrometer signal to calculate the temperature of the specific flue.

Benefits:

a. Using single sensor (pyrometer), temperature measurement of multipoint can be done.

b. Real time flue temperature measurement is being done.

Figure 27: Devices installed at Oven TOP.

Conclusion

The modernization of coke oven with use of new sensors have bring more visibility to the coke oven plant operation. The use of artificial intelligence to predict carbonization is instrumental in maintaining high productivity in coke ovens. The "advance heating control" and "battery health monitoring" model regulates the amount of heating energy, reducing energy consumption. This system also provides a quick and automatic response to operational issues, maintaining balanced battery temperatures. By addressing heating problems, this system helps to reduce emissions.

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