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Development of Virtual Training Platform for Tandem Cold Rolling Mill Using Data Science and Digital Twin Technology

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Abstract: ***An attempt has been made to develop Virtual Training Platform for Pickling Line Tandem Cold Mill (PLTCM) intended to deliver faster and enhanced learning experience of the process operator by leveraging Advanced Data Modelling, Data Science and Digital Twin Technology. Virtual Training Platform has modules for virtual tour of the plant, setup simulation, real-time rolling simulation, performance evaluation. Rolling Simulation has ANN based Automatic gauge control model and DNN based shape prediction model. Platform also comprises of a Natural Language Processing based chatbot for online query related to process line.***

Keywords: tandem cold Mill; Deep Neural Network (DNN); Virtual tour; Automatic Gauge Control (AGC), shape Control; chatbot

I. INTRODUCTION

In the age of agility and fast changing business scenario there is fast movement of people both in terms of location and job profile. People will need to know the requisite knowledge and develop the required skill set to maintain the existing level of operational efficiency. Classroom training is limited to theoretical aspects. Therefore, it's imperative to develop a simulator which will enable new operator/person to see what the impact are of changing various process parameter on rolling and give a feeling of the rolling environment. For the first time, Virtual Training Platform for Pickling Line Tandem Cold Mill (PLTCM), Tata Steel, Jamshedpur is developed for enhanced training experience. The objective is to enable virtual training platform for process operator for faster learning on process, controls checkout, plant start-up, rolling practice etc. by leveraging Advanced Modelling, Data Science and Digital Twin technology. PLTCM is five stands six high universal crown pickling line tandem cold mill. The process flow of PLTCM is shown in Fig. 1 below. The PLTCM receive coils produced by the Hot strip mill. The hot coils are brought into the Walking beam (WB) conveyor by the crane. The coils are moved from one support station to another support station of the WB conveyor Then the coils are moved to the Payoff reel by using the Coil car. The head portion of the new coil is brought into the Welder and welded to the previous coil. During welding operation, the entry section of the pickling line is stopped, while the middle section of the Pickling Line is kept running by wasting the accumulated coil for the Entry looper. The strip is then guided by various rolls into the Tension Leveler, which levels the tension in the strip by maintaining a preset elongation. Strip is then guided into the pickling tasks. In this section, the strip is submerged in acid. The strip is then accumulated at the #1 delivery looper to keep the running condition of Notcher and trimmer. The strip is then notched by the Notcher and trimmed at the sides by the Side trimmer. The strip is then accumulated at the #2 delivery looper to keep the running condition of Tandem cold mill. After center section, the coil enters the Tandem cold mill section to reduce the strip thickness to the desired preset value. The strip at the delivery side of the Tandem cold mill is then wound in any one of the Tension reels. The strip is then cut to desired length by the rotary shear at the delivery side of the Tandem cold mill. The cut coil is called the "CR coil".

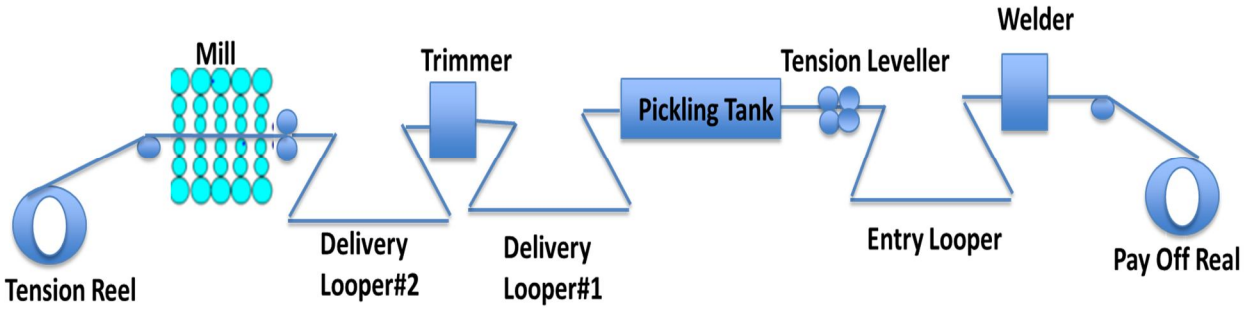


Fig.1- PLTCM Process flow

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PLTCM is fully automated line. Coil rolling schedule is downloaded to Level 2 from Manufacturing Execution System (MES). Coil rolling schedule in addition to rolling sequence contains coil data called Primary Data Input (PDI). PDI has information about input and output dimensions of the coil and other important information. Setup like welder setup, trimmer setup, tension setup, Mill setup is calculated in Level 2 and downloaded to Level 1 based on tracking events. Level 1 or PLC has Automatic gauge control (AGC) for achieving desired output thickness and automatic shape control for achieving target shape. From control desk Operator can change stop/start line, change mill speed. For shape control Operator can also change work roll bending, IMR bending, IMR shifting and mill levelling. Based on present training requirement for operator in PLTCM modules of Virtual training platform (VTP) is developed. Present work is specific to training of operators in Mill pulpit.

II. MODULES OF VIRTUAL TRAINING PLATFORM

The VTP has five modules shown in Fig. 2 covering important aspects of training -

A. Immersive Learning

M1: Virtual walk-through inside the plant

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B. Learning Through Reflection

M2: Material Tracking and PDI Data Management
M3: Setup Simulation with different input PDI
M4: Plant Simulation and Response
M5: Rolling Result Evaluation
M6: Chat Bot MITR- **M**anufacturing **I**ntelligent and Autonomous **T**eache**r**

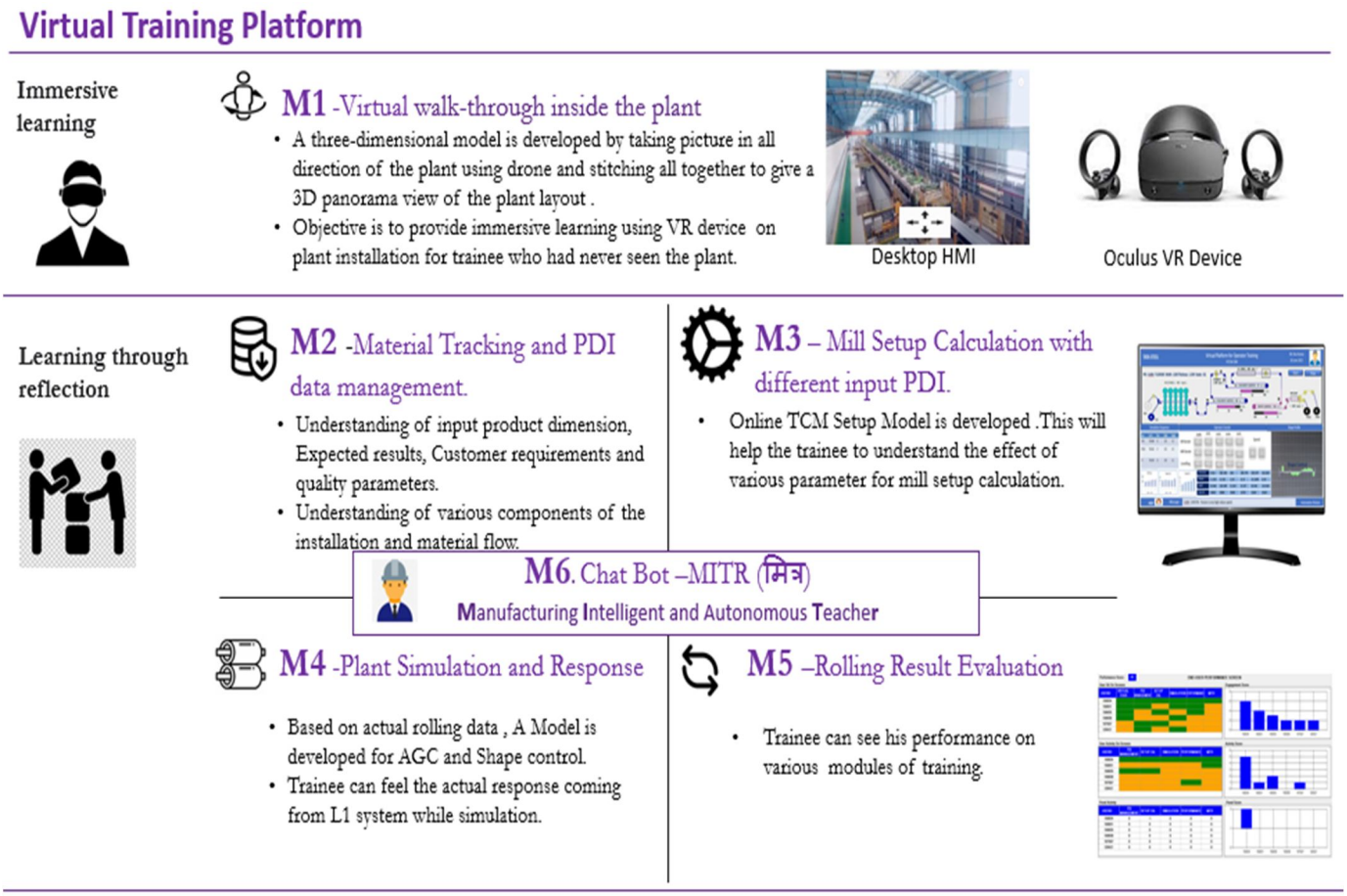


Fig. 2- Modules of VTP

III. TECHNOLOGIES USED

Virtual training platform is multiuser training platform. User application is packaged as one click installation on user laptop or PC from URL. User client application is developed in .net windows application. It is server client architecture, database and backgrounds model are running on centralised server. User can login application through authorised username & password.
Virtual training platform leverages Advanced Modelling, Data Science and Digital Twin technology. Technologies used in modules M1- M6 is shown in Fig .3 below.

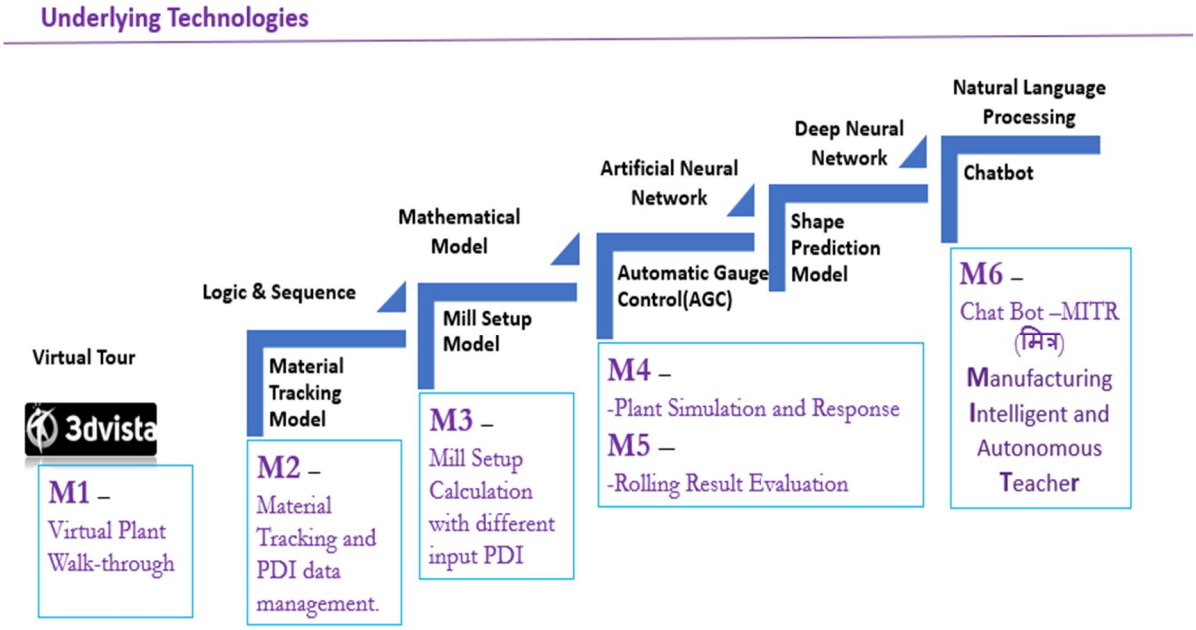


Fig. 3- Technologies used in Modules of VTP

A. M1: Virtual Tour of Plant

The purpose of this module is to give a virtual walk-through tour of the plant to trainee before going to the plant. Trainee can have 360 view of the plant layout, equipment, and process flow on his desktop or Virtual Reality (VR) device. In virtual walk through, trainee can navigate through each component of the process line. The labels and description are provided wherever applicable. Video files are also attached to get details understanding of the rolling process. Virtual tour is developed by capturing image of plant through drone imaging and stitching image together in 3D Vista package. Stitched image is then published in web URL and embedded to client user application. Virtual tour is embedded with voice over explaining various sections of plant, videos showing working of equipment, visual SOP's, and safety instruction. Virtual tour can also be done using Virtual Reality (VR) devices for enhanced experience. Fig. 4 shows snapshot of Virtual tour of plant.



Fig. 4-Virtual tour of Plant

B. M2: Material Tracking and PDI Data Management

The Objective of tracking module is to simulate material flow in line. It is most important module for integrated working of rolling simulator. Based on material tracking, target thickness and shape are passed to AGC model and shape prediction model. Material tracking model works on the principle of length balance and mass balance as shown in Fig. 5.

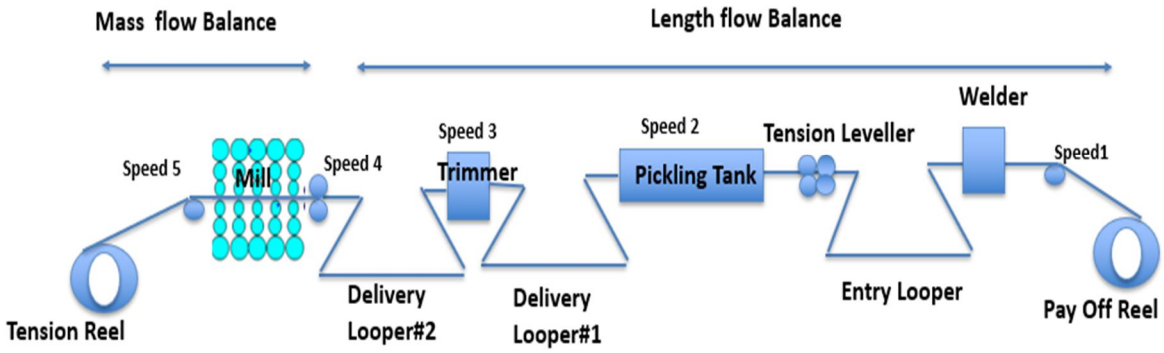
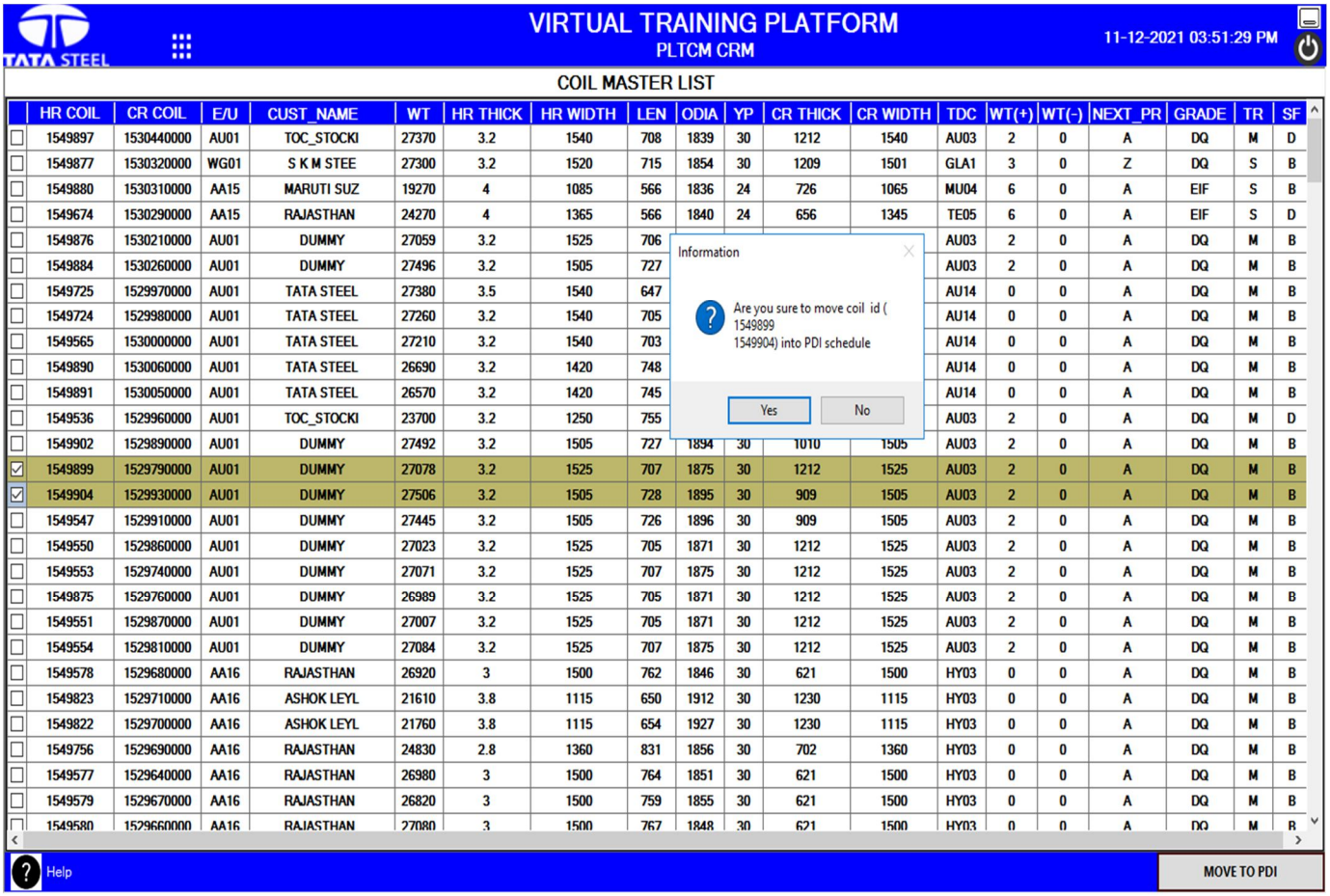


Fig.5 – Material Tracking concept

The PDI data management module objective is to make user understand rules of making rolling schedule which is part of their job. There is restriction on thickness jump, width jump and grade jump which trainee need to keep in mind before making rolling schedule. The Primary Data Input (PDI) of coil contains important information like coil dimensions, customer information etc. This module helps trainees in understanding of input product dimension, Expected results, Customer requirements and quality parameters. Fig. 6 shows Schedule making Screen.



	HR COIL	CR COIL	E/U	CUST_NAME	WT	HR THICK	HR WIDTH	LEN	ODIA	YP	CR THICK	CR WIDTH	TDC	WT(+)	WT(-)	NEXT_PR	GRADE	TR	SF
☐	1549897	1530440000	AU01	TOC_STOCKI	27370	3.2	1540	708	1839	30	1212	1540	AU03	2	0	A	DQ	M	D
☐	1549877	1530320000	WG01	S K M STEE	27300	3.2	1520	715	1854	30	1209	1501	GLA1	3	0	Z	DQ	S	B
☐	1549880	1530310000	AA15	MARUTI SUZ	19270	4	1085	566	1836	24	726	1065	MU04	6	0	A	EIF	S	B
☐	1549674	1530290000	AA15	RAJASTHAN	24270	4	1365	566	1840	24	656	1345	TE05	6	0	A	EIF	S	D
☐	1549876	1530210000	AU01	DUMMY	27059	3.2	1525	706					AU03	2	0	A	DQ	M	B
☐	1549884	1530260000	AU01	DUMMY	27496	3.2	1505	727					AU03	2	0	A	DQ	M	B
☐	1549725	1529970000	AU01	TATA STEEL	27380	3.5	1540	647					AU14	0	0	A	DQ	M	B
☐	1549724	1529980000	AU01	TATA STEEL	27260	3.2	1540	705					AU14	0	0	A	DQ	M	B
☐	1549565	1530000000	AU01	TATA STEEL	27210	3.2	1540	703					AU14	0	0	A	DQ	M	B
☐	1549890	1530060000	AU01	TATA STEEL	26690	3.2	1420	748					AU14	0	0	A	DQ	M	B
☐	1549891	1530050000	AU01	TATA STEEL	26570	3.2	1420	745					AU14	0	0	A	DQ	M	B
☐	1549536	1529960000	AU01	TOC_STOCKI	23700	3.2	1250	755					AU03	2	0	A	DQ	M	D
☐	1549902	1529890000	AU01	DUMMY	27492	3.2	1505	727	1894	30	1010	1505	AU03	2	0	A	DQ	M	B
☑	1549899	1529790000	AU01	DUMMY	27078	3.2	1525	707	1875	30	1212	1525	AU03	2	0	A	DQ	M	B
☑	1549904	1529930000	AU01	DUMMY	27506	3.2	1505	728	1895	30	909	1505	AU03	2	0	A	DQ	M	B
☐	1549547	1529910000	AU01	DUMMY	27445	3.2	1505	726	1896	30	909	1505	AU03	2	0	A	DQ	M	B
☐	1549550	1529860000	AU01	DUMMY	27023	3.2	1525	705	1871	30	1212	1525	AU03	2	0	A	DQ	M	B
☐	1549553	1529740000	AU01	DUMMY	27071	3.2	1525	707	1875	30	1212	1525	AU03	2	0	A	DQ	M	B
☐	1549875	1529760000	AU01	DUMMY	26989	3.2	1525	705	1871	30	1212	1525	AU03	2	0	A	DQ	M	B
☐	1549551	1529870000	AU01	DUMMY	27007	3.2	1525	705	1871	30	1212	1525	AU03	2	0	A	DQ	M	B
☐	1549554	1529810000	AU01	DUMMY	27084	3.2	1525	707	1875	30	1212	1525	AU03	2	0	A	DQ	M	B
☐	1549578	1529680000	AA16	RAJASTHAN	26920	3	1500	762	1846	30	621	1500	HY03	0	0	A	DQ	M	B
☐	1549823	1529710000	AA16	ASHOK LEYL	21610	3.8	1115	650	1912	30	1230	1115	HY03	0	0	A	DQ	M	B
☐	1549822	1529700000	AA16	ASHOK LEYL	21760	3.8	1115	654	1927	30	1230	1115	HY03	0	0	A	DQ	M	B
☐	1549756	1529690000	AA16	RAJASTHAN	24830	2.8	1360	831	1856	30	702	1360	HY03	0	0	A	DQ	M	B
☐	1549577	1529640000	AA16	RAJASTHAN	26980	3	1500	764	1851	30	621	1500	HY03	0	0	A	DQ	M	B
☐	1549579	1529670000	AA16	RAJASTHAN	26820	3	1500	759	1855	30	621	1500	HY03	0	0	A	DQ	M	B
☐	1549580	1529660000	AA16	RAJASTHAN	27080	3	1500	767	1848	30	621	1500	HY03	0	0	A	DQ	M	B

Fig. 6- Schedule making screen

C. M3: Setup Simulation with Different Input PDI

In setup simulation module trainee can see mill setup before rolling the coil. Trainee can also change coil PDI and see its effect on mill setup. Mill setup parameters [1,2] like roll force, tension, draft, max mill speed, roll gap change etc. are important and required for rolling. Mill setup parameters calculation is done with the coil specification, mill status information such as roll diameters etc. The basic purpose is to calculate the optimum reduction distribution among the five stands which will facilitate attaining the maximum rolling speed subject to the following constraints-

1) Balance of the Rolling Force in stands #1 and # 2
2) Balance of Motor Power of stands #2, #3, #4 and #5

A schedule calculated in this manner ensures maximum utilization of power and smooth rolling operation. Following figure shows the flow chart for set up calculation. Algorithm of setup optimisation is shown in flow chart in Fig 7.

In mill setup model commonly used equation in cold rolling like Hill's Equation is used for roll force calculation, Blank and Ford for forward slip calculation. Ford's equation is used for calculation of torque arm coefficient. Motor Power is calculated using equation 1. given below

$$H_P = 0.2192x10^{-3} \cdot (v / R) \cdot G_M / 1.34 \quad [KW] \quad (1)$$

G_M : Motor torque

R : Work roll radius

v : Rolling speed

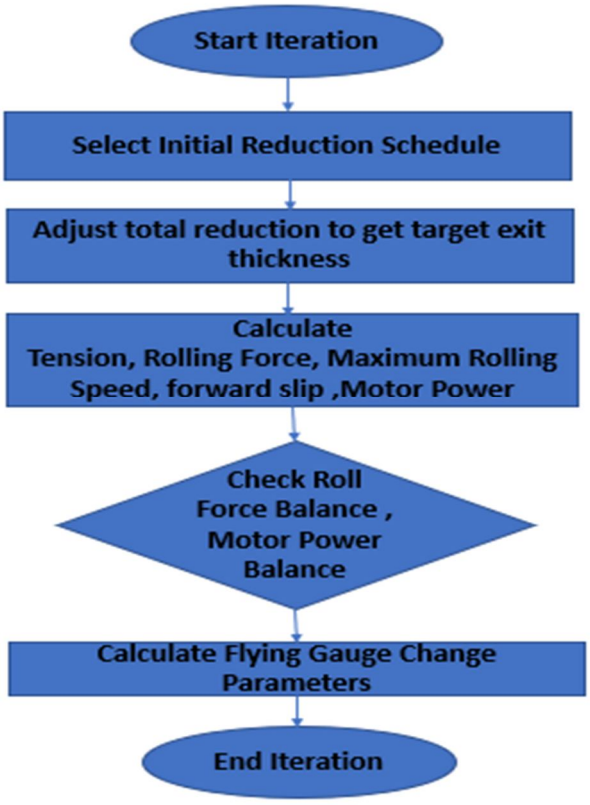
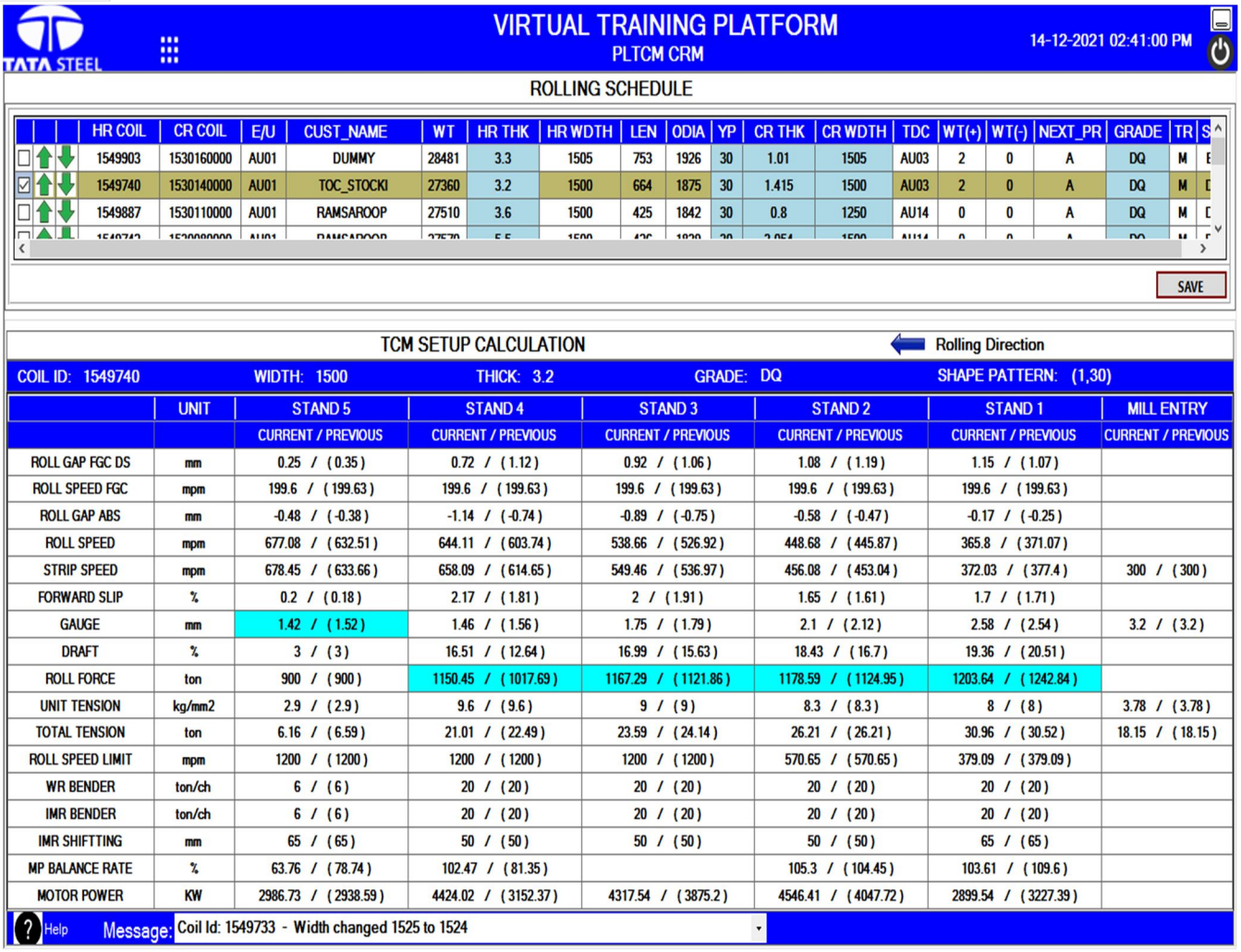


Fig. 7- Flowchart of setup Optimisation

The mill setup calculation is iterative process till condition for stable rolling and giving maximum throughput is satisfied. Fig. 8 shows setup simulation screen. Cyan colour highlights change in setup values between current/previous values.

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HR COIL	CR COIL	E/U	CUST_NAME	WT	HR THK	HR WDTH	LEN	ODIA	YP	CR THK	CR WDTH	TDC	WT(+)	WT(-)	NEXT_PR	GRADE	TR
1549903	1530160000	AU01	DUMMY	28481	3.3	1505	753	1926	30	1.01	1505	AU03	2	0	A	DQ	M
1549740	1530140000	AU01	TOC_STOCKI	27360	3.2	1500	664	1875	30	1.415	1500	AU03	2	0	A	DQ	M
1549887	1530110000	AU01	RAMSAROOP	27510	3.6	1500	425	1842	30	0.8	1250	AU14	0	0	A	DQ	M

	UNIT	STAND 5	STAND 4	STAND 3	STAND 2	STAND 1	MILL ENTRY
		CURRENT / PREVIOUS	CURRENT / PREVIOUS	CURRENT / PREVIOUS	CURRENT / PREVIOUS	CURRENT / PREVIOUS	CURRENT / PREVIOUS
ROLL GAP FGC DS	mm	0.25 / (0.35)	0.72 / (1.12)	0.92 / (1.06)	1.08 / (1.19)	1.15 / (1.07)	
ROLL SPEED FGC	mpm	199.6 / (199.63)	199.6 / (199.63)	199.6 / (199.63)	199.6 / (199.63)	199.6 / (199.63)	
ROLL GAP ABS	mm	-0.48 / (-0.38)	-1.14 / (-0.74)	-0.89 / (-0.75)	-0.58 / (-0.47)	-0.17 / (-0.25)	
ROLL SPEED	mpm	677.08 / (632.51)	644.11 / (603.74)	538.66 / (526.92)	448.68 / (445.87)	365.8 / (371.07)	
STRIP SPEED	mpm	678.45 / (633.66)	658.09 / (614.65)	549.46 / (536.97)	456.08 / (453.04)	372.03 / (377.4)	300 / (300)
FORWARD SLIP	%	0.2 / (0.18)	2.17 / (1.81)	2 / (1.91)	1.65 / (1.61)	1.7 / (1.71)	
GAUGE	mm	1.42 / (1.52)	1.46 / (1.56)	1.75 / (1.79)	2.1 / (2.12)	2.58 / (2.54)	3.2 / (3.2)
DRAFT	%	3 / (3)	16.51 / (12.64)	16.99 / (15.63)	18.43 / (16.7)	19.36 / (20.51)	
ROLL FORCE	ton	900 / (900)	1150.45 / (1017.69)	1167.29 / (1121.86)	1178.59 / (1124.95)	1203.64 / (1242.84)	
UNIT TENSION	kg/mm2	2.9 / (2.9)	9.6 / (9.6)	9 / (9)	8.3 / (8.3)	8 / (8)	3.78 / (3.78)
TOTAL TENSION	ton	6.16 / (6.59)	21.01 / (22.49)	23.59 / (24.14)	26.21 / (26.21)	30.96 / (30.52)	18.15 / (18.15)
ROLL SPEED LIMIT	mpm	1200 / (1200)	1200 / (1200)	1200 / (1200)	570.65 / (570.65)	379.09 / (379.09)	
WR BENDER	ton/ch	6 / (6)	20 / (20)	20 / (20)	20 / (20)	20 / (20)	
IMR BENDER	ton/ch	6 / (6)	20 / (20)	20 / (20)	20 / (20)	20 / (20)	
IMR SHIFTTING	mm	65 / (65)	50 / (50)	50 / (50)	50 / (50)	65 / (65)	
MP BALANCE RATE	%	63.76 / (78.74)	102.47 / (81.35)		105.3 / (104.45)	103.61 / (109.6)	
MOTOR POWER	KW	2986.73 / (2938.59)	4424.02 / (3152.37)	4317.54 / (3875.2)	4546.41 / (4047.72)	2899.54 / (3227.39)	

Fig. 8- Mill Setup Simulation Screen

D. M4: Plant Simulation and Response

This module contains Automatic Gauge Control (AGC) Model and shape prediction model. AGC model is used for achieving the desired output thickness without any Operator intervention. However, for shape control operator can give input like work roll bender, IMR Bender, IMR shift from control panel to get the desired coil output shape.

IV. AUTOMATIC GAUGE CONTROL

The AGC model is based ref [3]. The Gauge equation [4] of rolling can be represented as given in Fig 9. below.

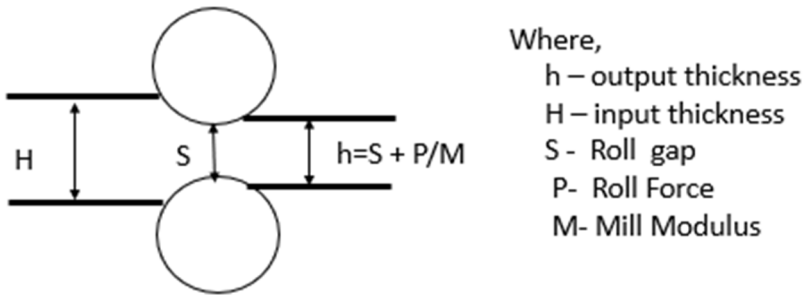


Fig. 9- Gauge Equation

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Any change in input thickness, friction, front tension, back tension, roll gap, material property can lead to variation in output thickness of coil as shown in Fig. 10 below. Operating point of rolling mill shifted from O to O' on change in input thickness (hi to hi') leading variation in output thickness(Δh). AGC changes roll gap, front tension & back tension to minimise this variation of output thickness.

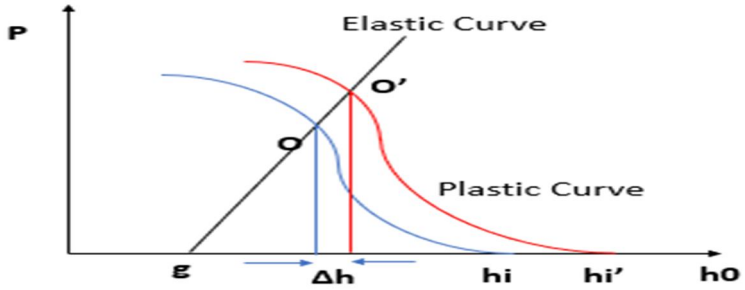


Fig. 10- Shifting of Mill Operating Point

Two Artifical Neural Network models are trained-

1) Thickness Prediction Model- To predict change in thickness due to variation input thickness, friction, front tension, back tension, roll gap.
2) Thickness Control Model – To find change in roll gap, front tension, back tension required to minimise variation in output thickness. Control variable is selected which leads to minimum changes.

A. Thickness Prediction Model

Actual rolling data is collected for around 5000 coils covering all grades and dimensions. A single layer ANN model is trained with input as Yield Stress(*Y*), friction coefficient(μ), Output thickness(*ho*), back tension(*tb*), front tension (*tf*) and output as Rolling Load(*P*) and rolling torque (*Tq*). Sensitivity factor[5] of inputs with respect to Rolling load(*P*) around operating point is found. In present work python jacobian function of autograd library is used for finding sensitivity factor. Equation 2 from ref [3] is directly used to find change output thickness due to change in roll gap, input thickness, front and back tension, friction, and Yield Stress. In this work, an ANN with a hidden layer is used. The ANN has 6: inputs, 2: outputs and 24: neurons in the hidden layer.

Following steps are followed in Thickness Prediction model -

- Train ANN model -$\{Y, \mu, ho, hi, tb, tf\} \xrightarrow{ANN} \{P, Tq\}$
- Find Sensitivity factor around operating point

$$\frac{\partial P}{\partial Y}\frac{\partial P}{\partial \mu}\frac{\partial P}{\partial h0}\frac{\partial P}{\partial hi}\frac{\partial P}{\partial tb}\frac{\partial P}{\partial tf}$$

- Calculate $\Delta h0$

$$\Delta h0 = \frac{W}{W - M\frac{\partial P}{\partial h0}}\left\{\frac{M\Delta g}{W} + \frac{\partial P}{\partial \mu}\Delta\mu + \frac{\partial P}{\partial tb}\Delta tb + \frac{\partial P}{\partial tf}\Delta tf + \frac{\partial P}{\partial y}\Delta y + \frac{\partial P}{\partial hi}\Delta hi\right\} \quad (2)$$

B. Thickness Control Model

Actual rolling data is collected for around 5000 coils covering all grades and dimensions. A single layer ANN model is trained with input as Yield Stress(*Y*), friction coefficient(μ), roll gap(*g*), input thickness (*hi*), back tension(*tb*), front tension (*tf*) and output as output thickness and Rolling Load(*Pb*).Sensitivity factor of inputs with respect to output thickness around operating point is found. In present work python jacobian function of autograd library is used for finding sensitivity factor. Equation 3,4,5 from ref [3] is directly used to find new control parameter value to minimize output thickness variation to zero. Parameter for control one out of (roll gap, back tension, front tension) is chosen which has minimum percentage change. . In this work, an ANN [6,7] with a hidden layer is used. The ANN has 6: inputs, 2: outputs and 28: neurons in the hidden layer.

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Following steps are followed in Thickness Control model -

- Train ANN Model -: $\{Y, \mu, g, hi, tb, tf\} \xrightarrow{ANN} \{ho, Pb\}$
- Find Sensitivity factor around operating point

  $\frac{\partial ho}{\partial Y}$ $\frac{\partial ho}{\partial \mu}$ $\frac{\partial ho}{\partial g}$ $\frac{\partial ho}{\partial hi}$ $\frac{\partial ho}{\partial tb}$ $\frac{\partial ho}{\partial tf}$

- Calculate Control Parameters

$$gf = g + \frac{\Delta ho}{\frac{\partial ho}{\partial g}} \quad (3)$$

$$tbf = tb + \frac{\Delta ho}{\frac{\partial ho}{\partial tb}} \quad (4)$$

$$tff = tf + \frac{\Delta ho}{\frac{\partial ho}{\partial tf}} \quad (5)$$

- Choose one with minimum changes

The above models are developed for all five stands and integrated together.

V. SHAPE PREDICTION MODEL

Actual rolling shape data is collected for around 500 coils covering all grades, dimensions, and shape pattern. In PLTCM shape is measured through shape meter having 32 channels (each channel of 52 mm width). Shape in 6 high tandem cold mills is controlled through IMR shift, work roll bending, IMR bending. Along with 32 channel output shape data, input parameters like IMR shift, work roll, IMR bending, roll force, reduction, mill levelling, tensions of all five stands are collected for training Deep Neural Network [8,9]. DNN is having 40 inputs, 32 outputs, 4 hidden layers with 100 neurons each.

A. Working of Rolling Simulation Screen

The Fig.11 shown below shows the snapshot of Rolling Simulation Screen. The trainee can start/stop the line with button given on top left corner of screen. The background material tracking model moves the coil in line based on line running speed. Line speed can be changed from Operator console. Mill sound is recorded and embedded in system, which increases /decreases with mill speed. Next to be rolled coil is welded in line when POR remaining length becomes zero. When next coil weld point reaches entry of mill stand#1, mill speed is automatically decreased and mill setup data for that coil is provided as input to AGC model and Shape model. AGC starts with initial values of mill setup like roll force, friction, tension, roll gap and tries to achieve target thickness by changing roll gap, front tension, back tension. Random small variation in input thickness, friction etc. is given to AGC model to get dynamic response. Similarly shape prediction model predicts shape based on initial setup data. Operator inputs from Operator console is passed to shape model to predict the output. System workflow is shown in figure below Fig 12.

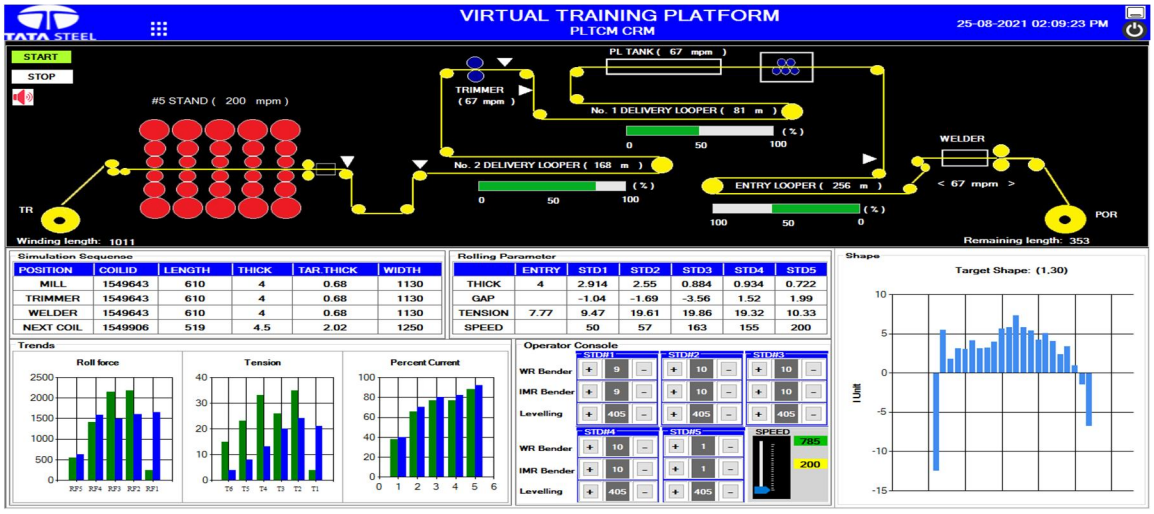


Fig. 11- Rolling Simulation Screen

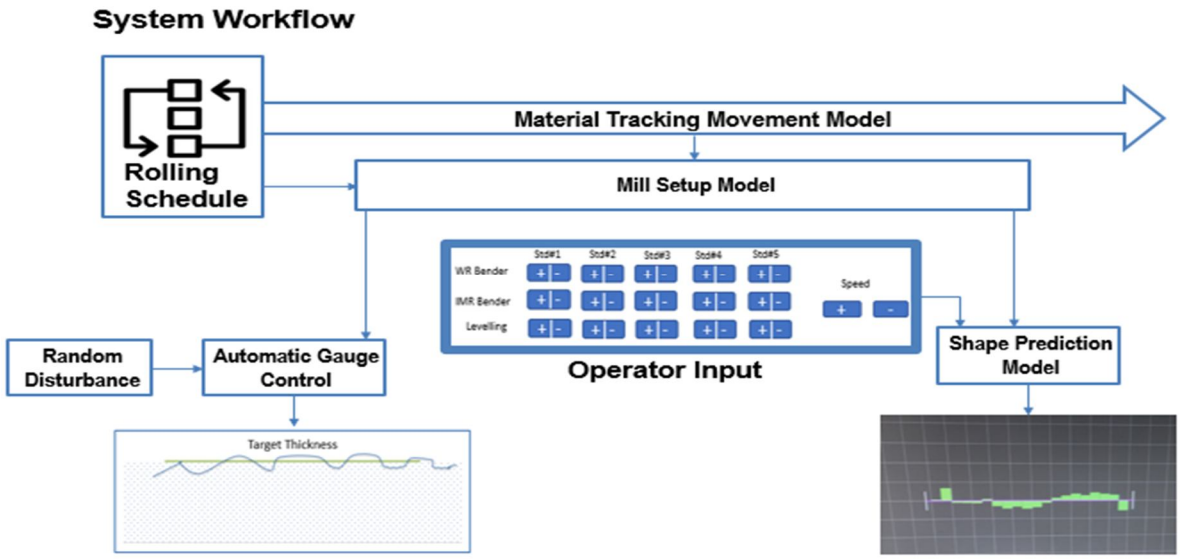


Fig. 12- Workflow of Rolling Simulation

B. M5: Rolling Performance Evaluation

The objective of this module is to evaluated training performance. The output thickness, tension, roll force, roll gap etc. of the coil rolled are stored in database of VTP. System also records modules covered by trainee and points are awarded accordingly. In case of wrong input by trainee is awarded negative points. Cumulative training score is calculated.



Fig. 13- Rolling Performance Evaluation

C. M6: Chatbot MITR- Manufacturing Intelligent and Autonomous Teacher

Virtual Training Platform is having Chat-Bot named MITR to provide online information to trainee. Trainee can query any information related to PLTCM line. Chatbot is designed to simulate conversation with human users of the desired subjects. There are different categories of chatbots such as Rule based, Independent and NLP based chatbot[10,11]. We are using NLP(Contextual) Chatbot**.** These are most advance chatbots, and combination of best of rule based and independent chatbots. These bots use NLP (Natural Language Processing) to understand the context and intent in users request and then acts accordingly. MITR uses following approach as shown in Fig 14.

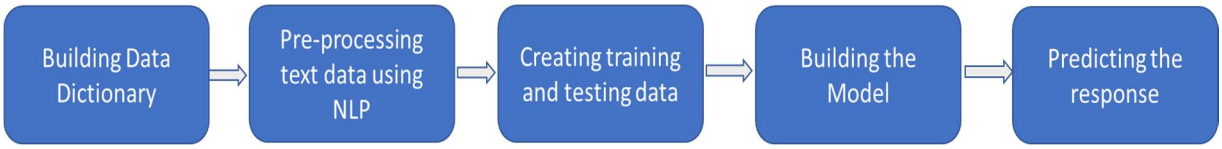


Fig. 14- NLP Based Approach

1) *Building Data Dictionary:* An intent file is created that captures intentions that which occur during interaction with chatbot. Then intent is labelled with a certain tag, for each tag we specify some patterns of how a user poses a query to chatbot. Model will later use these inputs after pre- processing these data to train itself, to identify right intent when user poses a query.
2) *Data pre-processing using NLP:* For pre-processing text data, we used Natural language processing NLP), NLTK (Natural language toolkit) is a platform in python which facilitates application of same. It involves handling of upper case/lower case letter and removal of noise, Tokenization, stemming, Lemmatization and bag of words.
3) *Model Building:* A list of classes containing information of tags is created, similarly list of patterns is also created. Deep neural network sequential model using tensor flow API is built on the data. Some dropout layers also used to prevent the model overfitting on Data input.

Interaction with Chatbot

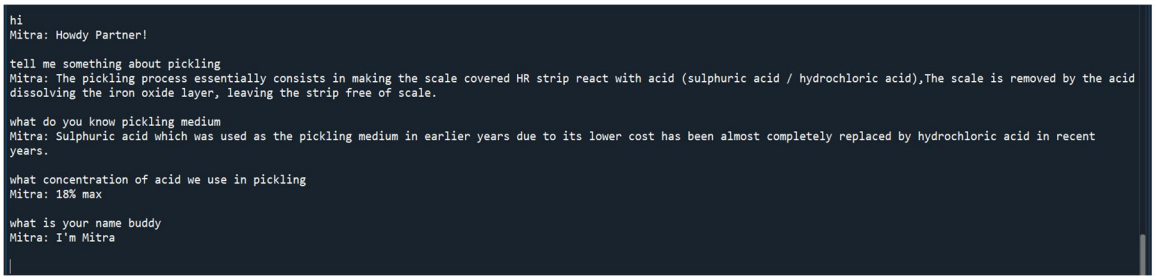


Fig.15- Interaction with Chatbot

VI. CONCLUSION AND FUTURE WORK

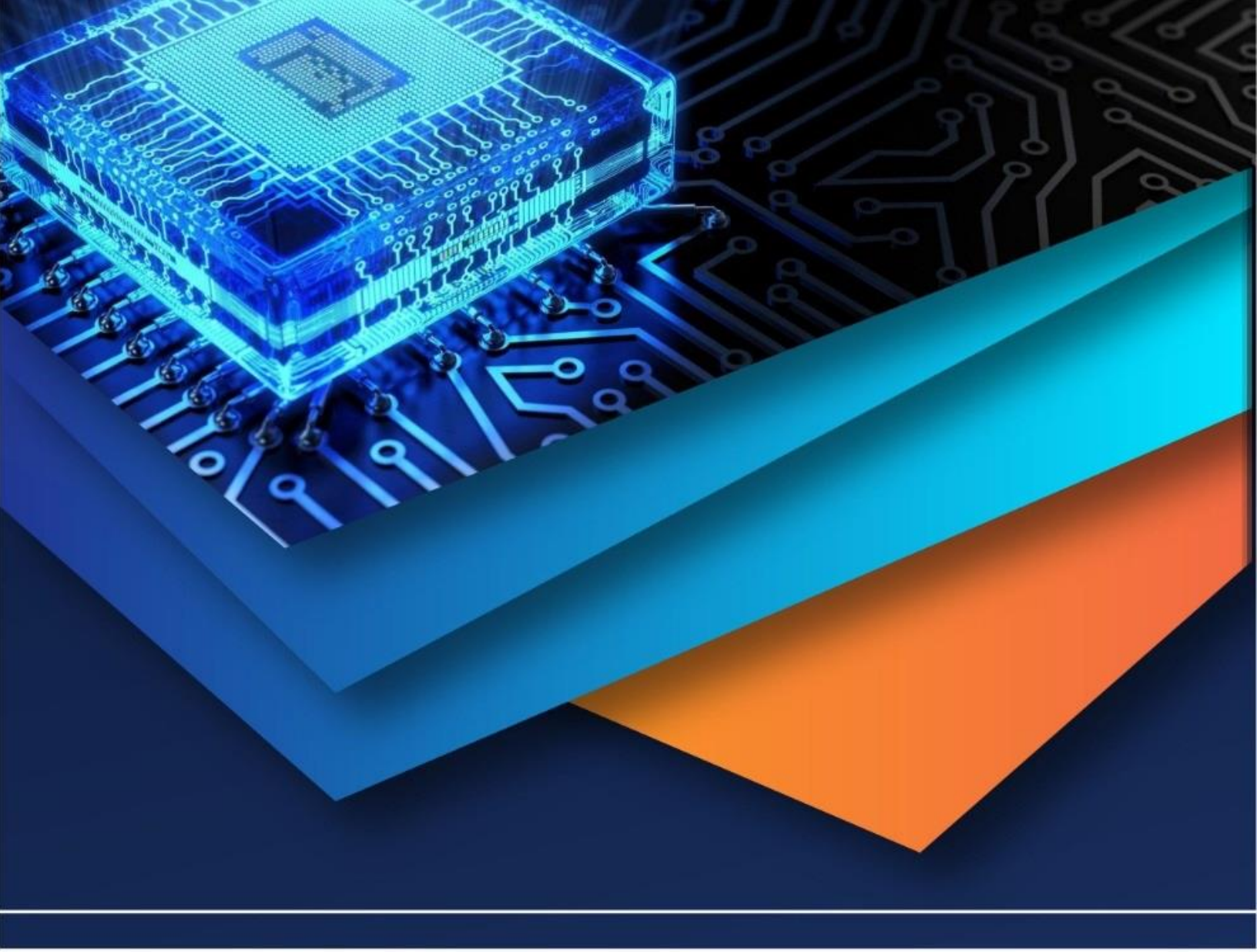
An effort has been made to develop the virtual training platform leveraging both the classical and machine learning based techniques to deliver a unique experience to the user. The simulator can give a feeling of the actual rolling environment with learning regards to model behaviour and operator intervention and see the impact first-hand. This can be used to train people virtually without coming to plant through the virtual tour and with the help of information boxes, a user can interactively gain a first-hand experience of the shop floor. This can be used as a tool to reduce cycle time for effective learning and training.

VII. ACKNOWLEDGEMENT

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