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Power Consumption Reduction Of A Main Nitrogen Compressor Of An Air Sepration Unit Using DMAIC Phases

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Abstract- *As the saying goes, "Power saved is Power generated" it is very essential for every industry to reduce and improve in the field of power consumption as its one of the largest operating cost for any industry and in particular to an air separation unit where raw material is air which is available free of cost from the environment. By applying Industrial Engineering tools it is aimed to reduce power consumption of an equipment named Main Nitrogen Compressor of an air separation unit of an xyz company by identifying the scope of reducing power consumption. Main nitrogen compressor is used to increase the pressure of nitrogen by compressing it in three stage centrifugal compressor and this compressed nitrogen is sent to booster nitrogen compressor along with medium pressure nitrogen also called Shelf gaseous nitrogen (ShelfGAN) clubbed. The flow of ShelfGAN into booster nitrogen compressor is determined such that net power saving of* ***227.12*** *kW/hr is achieved for a main nitrogen compressor by adopting a problem solving methodology called DMAIC(Define-Measure-Analyze-Improve-Control) which is a data-driven strategy, it is implemented by drafting in detail steps in order to shift our focus from the output performance (y) that is MNC power consumption to the root causes(x's). Based on these steps, data pertaining to MNC power consumption is collected and is transferred into a statistical problem (i .e., mapping x and y) and a statistical solution that is by solving y = f (x) by means of multiple regression analysis and then the statistical solution is transferred into a practical solution.*

Keywords- *Main Nitrogen Compressor(MNC) Power Consumption, Booster Nitrogen Compressor(BNC), Shelf Gaseous Nitrogen(ShelfGAN), Define, Measure, Analyze, Improve, Control.*

I. INTRODUCTION

The aim of this paper is to reduce the power consumption of a main nitrogen compressor(MNC) of an air separation unit(ASU) of an xyz industry and improve the productivity by using Industrial engineering tools and techniques. Power consumption is the single largest operating cost incurred by an air separation unit which in turn has it's direct impact on productivity. In an ASU the raw material is air which is available free of cost from the environment, hence power consumption being largest operating cost incurred by running an ASU a need for minimizing it is present. Generally during production, most likely the product nitrogen gas produced has to be supplied to customers or filling stations it has to be supplied at higher pressure for which a 3 stage centrifugal compressors are used as main nitrogen compressor(MNC) which increases the pressure of a low pressure nitrogen from 1.05 bar to medium pressure nitrogen of 6 bar and this 6 bar pressured nitrogen gas is clubbed with flow of a shelf gaseous nitrogen(ShelfGAN) which is also at 6 bar of pressure and this mixture is sent to booster nitrogen compressor(BNC) to increase the pressure from 6 bar to 19 bar. In this process of increasing the pressure in two phases using two different capacity compressors there exists a scope for improvement that is power consumption reduction by optimizing the flow of shelf gaseous nitrogen into BNC so that volume of air compressed by MNC decreases thereby decreasing MNC power consumption.

Using DMAIC methodology a detail process study is made and key process input variables(KPIV) and key process output variables(KPOV) were identified and data pertaining to it is collected for the period of three months and then and Multilinear equation was set using Minitab 17 statistical software in order to quantify the amount of power saved by increasing the flow of shelf gaseous nitrogen into booster nitrogen compressor and then there implications on other factor as waste nitrogen purity level percentage and lower column pressure is studied and net savings is calculated for carrying out this project DMAIC methodology was chosen as it is data driven strategy which leads to step by step process without any prejudice in a stage wise manner.

II. LITERATURE REVIEW

There have been various literatures on DMAIC methodology for analysing and implementing it in order to solve the problem

Jeoren de Mast et al. [1], gives insights to DMAIC model functions as a problem structuring device. It breaks down a problem solving task into a sequence of generic subtasks, represented and defined by the Define-Measure-Analyze-Improve- Control stages. More detailed accounts breakdown these subtasks into more specific deliverables.

Liwei Yan1 et al. [2] carried out literature review on Air separation unit on a large scale glancing on process of air separation and opportunities in reducing power consumption in detail . Their study showcase the importance of power consumption in an air separation unit.
Douglas C. Montgomery [3] [4] in his works sited the fundamentals of statistics and analysis for better understanding of data using different tools and techniques to gauge and study the behavior pattern in order to have a clear perspective on analyzing data.

Michael H. Kutner et al.[5] in his work made a detailed study on multiple regression analysis fundamentals and predictive model building with which analysis on historical data is done.

III. METHODOLOGY

The DMAIC model is a set of tools outlined in five phases that are used to characterize and optimize industrial processes and it is done in five phases in chronological order[6]

3.1 Define

In define phase problem statement is defined and identified for improvement.

3.1.1 Problem statement. As power consumption is a largest operating cost for an Air Separation Unit(ASU) efforts are made in the direction to reduce the power consumption of a Main Nitrogen Compressor (MNC)

3.1.2 Problem objective. The objective is to reduce power consumption of a Main Nitrogen Compressor(MNC) by

- Optimize the flow of Shelf Gaseous Nitrogen(ShelfGAN) into Booster Nitrogen Compressor(BNC)
- Implications on optimizing the flow of shelf gaseous nitrogen on other factors as lower column pressure and waste nitrogen purity percentage.

3.2 Measure

The measure phase determines the target performance of the process, defines input and output variables of the process.
3.2.1 Process mapping. Process mapping identifies the flow of events in a process as well as the inputs(x's) and outputs(y's) in each step of a process

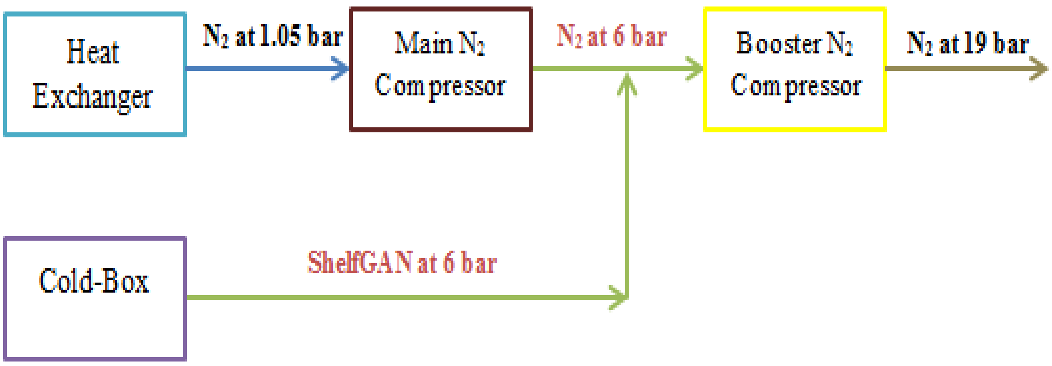

Figure 1. Process Mapping for MNC Power Reduction

After distillation process the product nitrogen is sent to compressors in order to meet the customer required pressure hence as shown in the above figure 1 low pressure nitrogen that is at 1.05 bar from heat exchanger is sent to main nitrogen compressor which is a three stage centrifugal compressor which compresses nitrogen to achieve 6 bar pressure which in turn sent to booster nitrogen compressor along with the medium pressure nitrogen called as shelf gaseous nitrogen produced from lower column of a cold box to attain high pressure of 19 bar .

3.2.2 Key process output variables(KPOV) and Key process input variables(KPIV). On brainstorming the key output and input variables for a main nitrogen compressor power consumption are found to be the booster nitrogen compressor input, flow of shelf gaseous nitrogen is considered along with other parameters considered for data collection are lower column pressure, and waste nitrogen purity. Hence data is collected pertaining to above factors with key process output variable(KPOV) as main nitrogen compressor electric power.

3.2.3 Data Collection. Data is collected in the form of daily production report(DPR) that is data pertaining to the production and process of compression of low pressure nitrogen of a main nitrogen compressor are collected which is stored in database as shown in table 1

Table 1. Data pertaining to MNC power consumption

Days	BNC Input in Nm^3/hr	ShelfGAN in Nm^3/hr	MNC Power in kW/hr	Waste N_2 Purity in %	Lower column pressure in bar
1	43970	11570	4741	0.465	4.36
2	45827	12310	4883	0.562	4.49
3	45897	11720	4904	0.497	4.54
4	45020	12260	4788	0.548	4.52
5	45985	12870	4856	0.583	4.48
6	45538	12020	4869	0.576	4.51
7	44215	11140	4774	0.467	4.37
8	43635	11410	4703	0.485	4.28
9	42610	11130	4617	0.459	4.21
10	42353	11040	4626	0.448	4.20
11	42275	11830	4563	0.556	4.21
12	41527	12140	4477	0.602	4.22
13	43006	11670	4621	0.514	4.17
14	42030	11540	4543	0.506	4.19
15	43050	11540	4672	0.512	4.23
16	44500	14080	4717	0.668	4.10
17	43421	14520	4595	0.581	4.07
18	43463	14670	4533	0.548	4.07
19	42698	15000	4446	0.497	4.05
20	42656	14680	4477	0.584	4.04
21	42057	14020	4402	0.470	4.03
22	42497	15340	4419	0.416	4.03
23	43228	15630	4468	0.442	4.05
24	44201	15780	4607	0.443	4.08
25	43519	16020	4479	0.439	4.05
26	43030	16950	4391	0.484	4.01
27	43699	16280	4433	0.652	4.04
28	47045	16640	4753	0.706	4.17
29	48185	17670	4859	0.689	4.19
30	43838	17880	4451	0.543	4.01
31	43375	17670	4431	0.667	4.01
32	43950	17590	4489	0.645	4.10
33	47050	17890	4767	0.693	4.20
34	49671	17470	4965	0.967	4.28
35	49766	17100	5052	0.646	4.29
36	43531	18220	4379	0.723	4.06
37	45016	18540	4518	0.745	4.18
38	47670	18500	4775	0.762	4.26
39	46565	18670	4662	0.710	4.20
40	46367	17930	4651	0.640	4.26
41	45912	18340	4610	0.685	4.21
42	45155	18140	4546	0.591	4.17
43	44175	17050	4499	0.579	4.18
44	44076	17990	4479	0.560	4.09
45	44269	18390	4453	0.802	4.03
46	45985	18140	4604	0.781	4.28
47	45829	16990	4653	0.756	4.20
48	44731	17460	4517	0.615	4.11

49	44925	18620	4486	0.827	4.09
50	44325	18090	4468	0.644	4.07
51	42956	16740	4403	0.591	4.06
52	45459	17100	4634	0.862	4.24
53	43729	16040	4500	0.697	4.29
54	42575	15640	4450	0.740	4.24
55	42692	15770	4470	0.737	4.22
56	43358	15900	4478	0.684	4.24
57	43500	16010	4487	0.654	4.30
58	43332	16030	4507	0.707	4.25
59	47812	17570	4882	0.699	4.23
60	47257	18170	4777	0.825	4.19
61	46985	18590	4756	0.864	4.18
62	46986	18840	4708	0.856	4.22
63	46221	16840	4733	0.753	4.22
64	46429	17600	4713	0.721	4.21
65	46135	18480	4624	0.886	4.14
66	44793	19090	4466	0.894	4.06
67	44315	17940	4494	0.658	4.15
68	46871	18130	4737	0.785	4.28
69	44747	17830	4515	0.746	4.15
70	47388	16780	4832	0.730	4.18
71	48434	18930	4808	0.886	4.33
72	45460	17970	4553	0.710	4.23
73	48980	18400	4884	0.865	4.32
74	50036	18460	4981	0.884	4.33
75	49003	18870	4863	0.796	4.27
76	46422	18180	4645	0.774	4.26
77	48630	17720	4897	0.795	4.25
78	48495	16190	4945	0.692	4.29
79	48956	16000	5019	0.713	4.27
80	49097	16050	5025	0.702	4.31
81	46625	16980	4711	0.764	4.29
82	45800	16710	4652	0.746	4.20
83	45626	17140	4621	0.543	4.20
84	46298	17510	4675	0.644	4.21
85	46249	15910	4748	0.676	4.31
86	49790	18990	4956	0.901	4.38
87	50492	18140	5049	0.897	4.17
88	48926	18740	4855	0.899	4.34
89	46784	18010	4689	0.862	4.28
90	50144	17090	5037	0.845	4.32
91	49995	16870	5047	0.815	4.21
92	47969	17890	4813	0.880	4.30
93	47100	17800	4737	0.732	4.29
94	48361	18420	4782	0.790	4.38
95	50131	19130	4953	0.906	4.36
96	51061	18660	5099	0.875	4.40

3.3 Analyse

The analyze phase uses data to establish the key process inputs that affect the process outputs[7]

3.3.1 Detailed Process mapping for tracing KPIV. For reducing the electric power consumption of a main nitrogen compressor flow of shelf gaseous nitrogen is to be optimized and quantified for electric power saving as shown in the figure

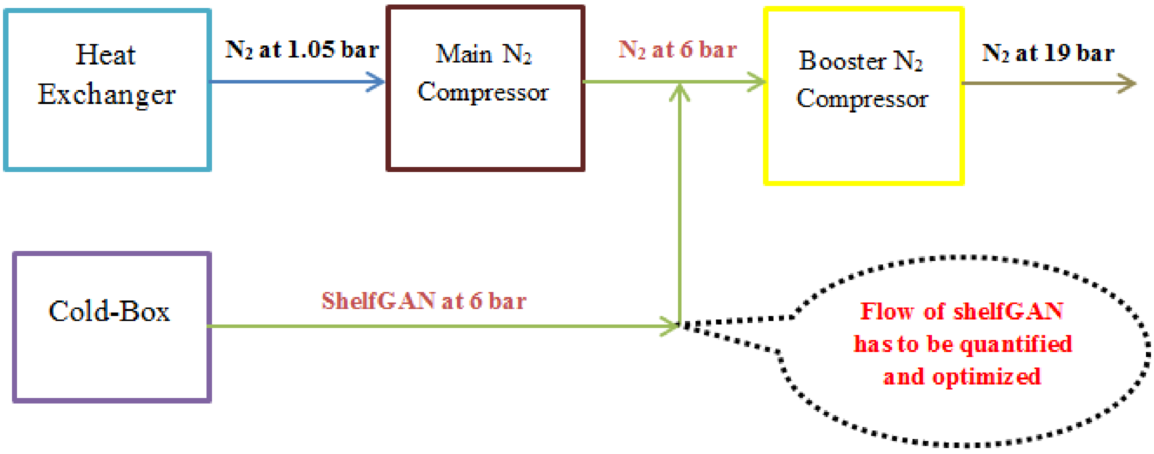

Figure 2.Detailed process mapping for flow of shelfGAN

From the figure 2 it can be demonstrated that the on clubbing MNC discharge and shelfGAN we get the amount of BNC input that has to be compressed that is

Booster compressor input = (MNC Discharge + Flow of ShelfGAN)

As our key process output variable is main nitrogen compressor electric power consumption which depends upon the amount of nitrogen it has to compress that is

MNC Power α MNC Discharge

MNC Power is directly proportional to MNC discharge and MNC discharge is inversely proportional to flow of shelf gaseous nitrogen that is

MNC Discharge $1/\alpha$ Flow of ShelfGAN

Hence by varying the flow of shelf gaseous nitrogen, MNC power consumption can be reduced which has to be quantified in next steps.

3.4. Improve

The improve phase identifies the improvements to optimize the outputs. It identifies x's and determines the y = f(x) relationship, and statistically validates the new process operating conditions.

3.4.1 Building the multiple regression model: The proposed multiple regression model is

$$Y = C + B_1 X_1 + B_2 X_2 \qquad (1)$$

where

Y: MNC power in kW/hr

X_1: BNC input in Nm^3/hr

X_2: ShelfGAN in Nm^3/hr

In this model, the criterion variable is MNC power and the predictor variables are BNC input and ShelfGAN. Because these variables are controllable parameters, they can be used to predict the MNC power consumption. A commercial statistical package Minitab 17 was used to do the regression analysis and a regression equation has been set for the data shown in table 1 as

$$Y = 1159.6 + 0.09321 X_1 - 0.04519 X_2 \qquad (2)$$

A statistical model was created by regression function in Minitab 17 from the set. The R Square was 0.9860, which showed that 98.60 % of the observed variability could be explained by the independent variables. The R Square adjusted is 98.57 % and R Square predicted is 98.53 %, the significance level was based on the P-value as insignificant if $P > 0.10$, significant if $P < 0.10$ as $P < 0.10$ both the parameters are significantly effective for MNC power consumption.

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Model Summary

S         R-sq     R-sq(adj)   R-sq(pred)
22.732   98.60%    98.57%      98.53%


Coefficients

Term            Coef     P-Value
Constant      1159.6      0.000
BNC Input    0.09321      0.000
ShelfGAN    -0.04519      0.000
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Figure 3. Model summary and p-values for the set model

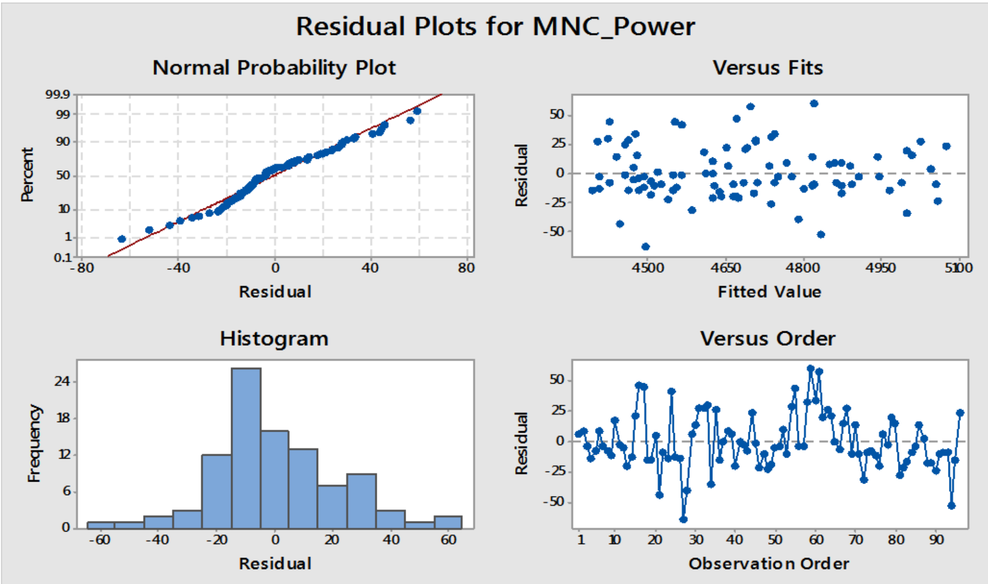

Figure 4.Residual plots for MNC power

Minitab generates residual plots as shown in the figure 3 which is used to examine the goodness of model fit. Residual is the difference between an observed value (y) and its corresponding fitted value (ŷ) and they indicate the extent to which a model accounts for the variation in the observed data. As the residuals form a straight line they are normally distributed and in versus fits as there is no recognizable pattern there is no error due to random, histogram shows the spread of variation which is well within the limit.

3.4.2 Analysis by setting parameters on different levels. ShelfGAN is set at three different levels as 11000, 15000, 19000 and for different BNC input ranging 43000, 45000, 47000 are analyzed by putting in equation as MNC_Power = 1159.6 + 0.09321 BNC Input - 0.04519 ShelfGAN

Table 2. Data pertaining to MNC power consumption

BNC Input	ShelfGAN in Nm^3/hr	MNC power in kW/hr
43000	11000	4670.54
	15000	4489.78
	19000	4309.02
45000	11000	4856.96
	15000	4676.20
	19000	4495.44
47000	11000	5043.38
	15000	4862.62
	19000	4681.86

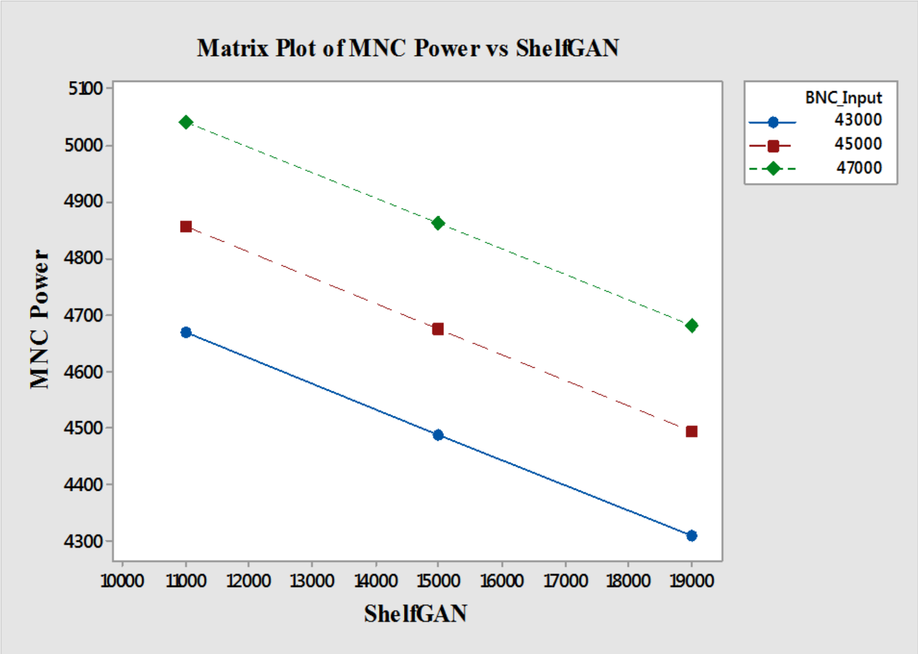

Figure 5. Matrix plot of MNC power on increasing ShelfGAN

MNC power has been reduced by 5043.38 – 4681.86 = **361.52 kW/hr** on increasing shelfGAN from 11000 Nm^3/hr to 19000 Nm^3/hr keeping BNC_Input as 47000 Nm^3/hr
From the figure 5 it is seen that for different BNC Input there is an equal amount of decrease of power consumption of 361.52 kW/hr

3.4.3 Implications on other factors on increasing ShelfGAN. On increasing the flow of ShelfGAN from 11000 Nm^3/hr to 19000 Nm^3/hr we need to check the implications on other factor as lower column pressure and waste nitrogen purity which is done using matrix plot as shown in figure 6

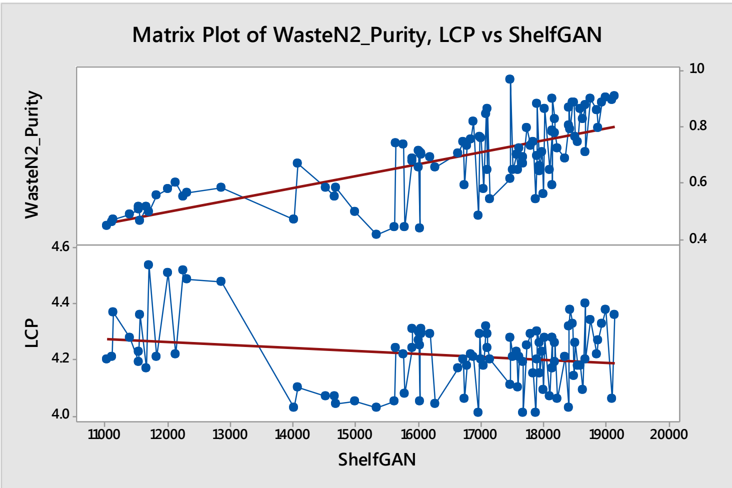

Figure 6. Implication on other factors

From the figure 5 as we can see with increase in ShelfGAN there is increase in waste nitrogen purity level which accounts for loss of power in terms of oxygen molecules which has been let out and there is decrease in lower column pressure which is beneficial from production point of view though it doesn't account for power consumption.

3.5 Control

3.5.1 Monetary calculations for waste nitrogen purity. A regression model is set using Minitab 17 statistical software with waste nitrogen purity as predictor variable and BNC input and ShelfGAN as independent variables are selected as the waste nitrogen purity accounts for oxygen molecules present, higher the molecules of oxygen left into nitrogen waste gas the power consumed for producing it will be lost.

Regression Equation

$$WasteN2\_Purity = -0.977 + 0.000026\ BNC\ Input + 0.000028\ ShelfGAN$$

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0815376	66.24%	65.51%	64.28%

Coefficients

Term	Coef	P-Value
Constant	-0.977	0.000
BNC Input	0.000026	0.000
ShelfGAN	0.000028	0.000

Figure 7. Model summary and p-values for the set model

As the p-value is equal to zero BNC input and ShelfGAN play a vital role in predicting the waste nitrogen level.

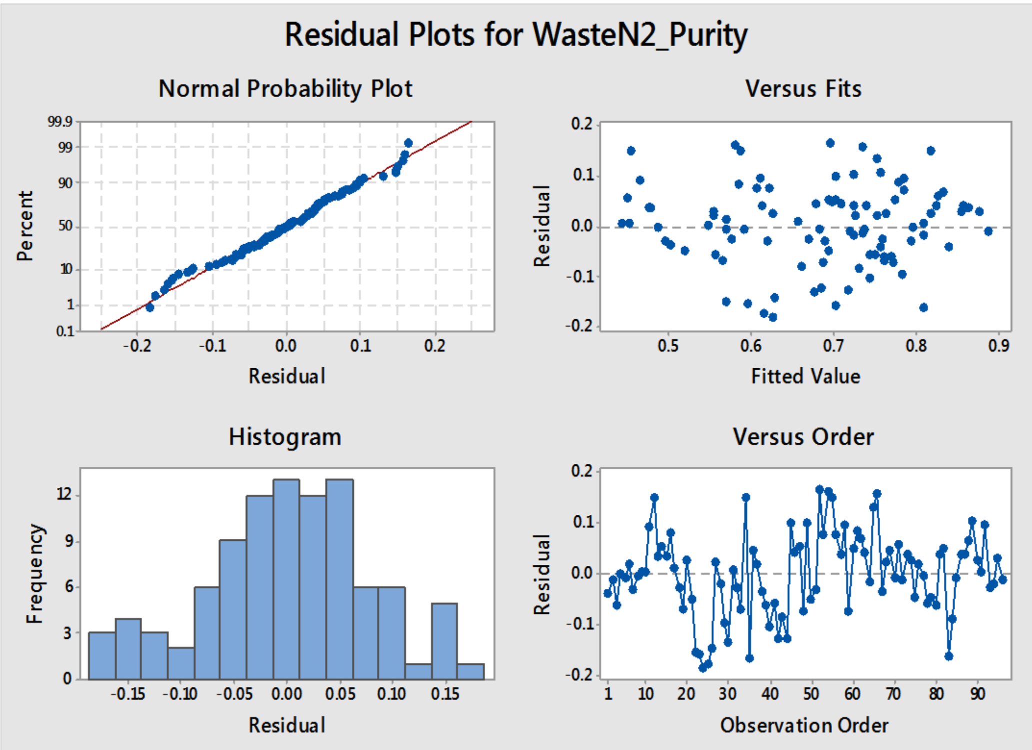

Figure 8.Residual plots for Waste nitrogen purity

As the residuals form a straight line they are normally distributed and in versus fits as there is no recognizable pattern there is no error due to random, histogram shows the spread of variation which is well within the limit.

ShelfGAN is set at three different levels as 11000, 15000, 19000 and for different BNC input ranging 43000, 45000, 48000 are analyzed by putting in equation

$$WasteN2\_Purity = -0.977 + 0.000026\ BNC\ Input + 0.000028\ ShelfGAN$$

Table 3. Data pertaining to Waste Nitrogen Purity

BNC Input in Nm^3/hr	ShelfGAN in Nm^3/hr	Waste nitrogen purity in %
43000	11000	0.449
	15000	0.561
	19000	0.673
45000	11000	0.501
	15000	0.613
	19000	0.725
47000	11000	0.553
	15000	0.665
	19000	0.777

With increasing shelfGAN there is substantial increase in waste nitrogen purity levels which has to be calculated and it is very essential to know that there is increase in waste nitrogen purity with increase in BNC Input but it depends upon customers requirement on the other hand flow of shelfGAN can be varied from 11000 to 19000 Nm^3/hr. Hence analysis and calculations are to be done for increasing airflow rather than increasing BNC Input.

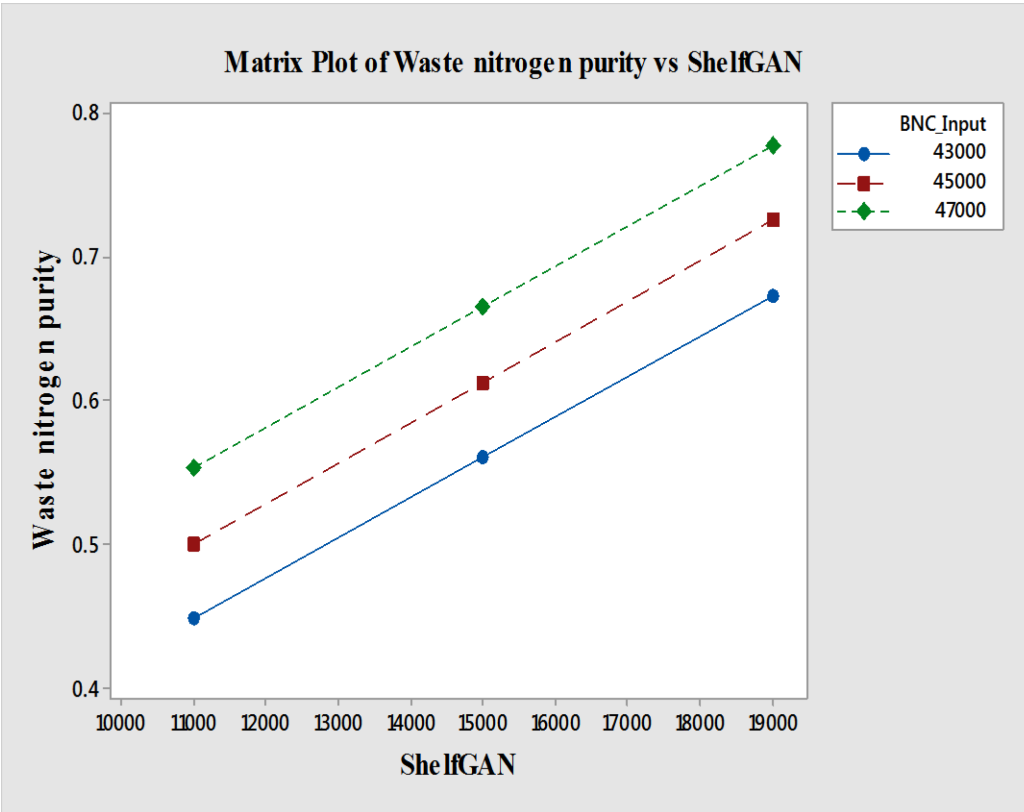

Figure 9.Matrix plot of waste nitrogen purity

Waste Nitrogen Purity has been increased by (0.777-0.553) = **0.224 %** on increasing shelfGAN from 11000 Nm^3/hr to 19000 Nm^3/hr keeping BNC_Input as 47000 Nm^3/hr. Waste nitrogen purity accounts for loss of oxygen molecules which in turn has its effect on loss of power which is consumed to produce oxygen molecules that are present in nitrogen gas produced and for 1 % increase in waste nitrogen purity 63 kW/hr of power has been spent wasted. Hence 134.4 kW/hr of power has been lost on increasing the flow of ShelfGAN from 11000 Nm3/hr to 19000 Nm3/hr.

IV. RESULTS

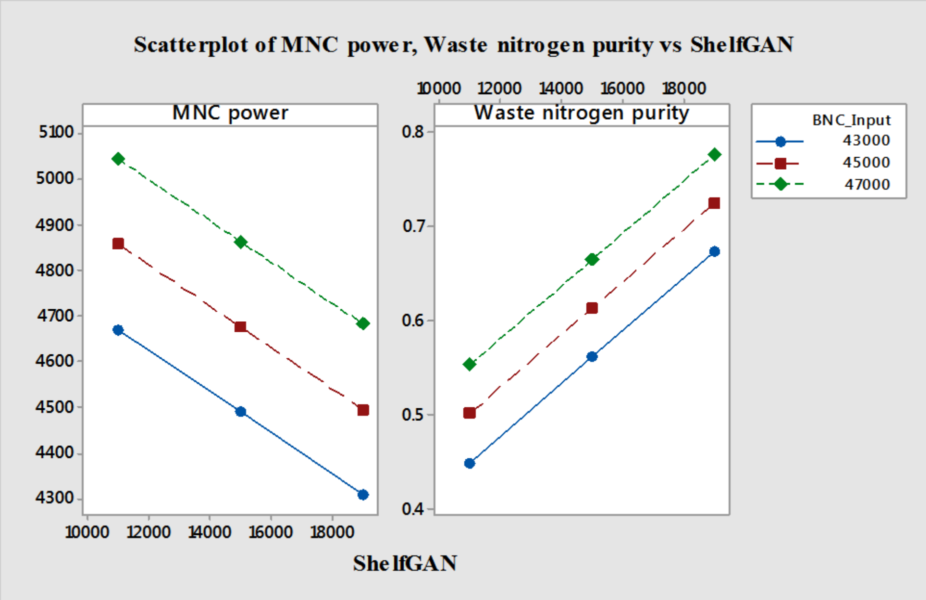

Figure10 .Comparing MNC power and waste N_2 purity

The amount of power saved by increasing ShelfGAN from 11000 Nm^3/hr to 19000 Nm^3/hr at various BNC Input of 43000, 45000 and 47000 is 361.52 kW/hr and power lost due to increase in waste nitrogen purity is 134.4 hence net power saving is **361.52-134.4 = 227.12** kW/hr

V. CONCLUSION

The important conclusions drawn from the present work are summarized as follows:

1. Main Nitrogen Compressor power consumption is reduced by 227.12 kW/hr by increasing the flow of Shelf gaseous nitrogen into booster nitrogen compressor from 11000Nm^3/hr to 19000Nm^3/hr

2. On increasing the flow of ShelfGAN there is increase in waste nitrogen purity and leads to minimal loss of power which is in acceptable range

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