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Energy Consumption Optimization based on Design of Experiments integrated Six Sigma: A Case Study on Indian Galvanizing Industry

Niharika Choubey[1], Neha Verma[2]

[1]M. Tech student, Department of Mechanical Engineering SSIPMT, Raipur (C.G.), India
[2]Assistant Professor, Department of Mechanical Engineering SSIPMT, Raipur (C.G.), India

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Abstract - *The galvanizing industries major amount of energy in the form of electricity, liquefied petroleum gas, or by using natural gases. A major amount of these energy sources are consumed by the products due to over-processing, a high cross-section of products, and rejection or rework of the product. To study the major causes of this energy exploitation in the hot-dip galvanizing industries a case study has been carried out on an Indian galvanizing industry in this paper. The liquefied petroleum gas (LPG) is used to keep zinc in a liquid phase in a zinc bath. Six Sigma's DMAIC methodology is approached for energy consumption optimization by utilizing the single factorial Design of Experiments technique. The two factors over-processing & high cross-sectional weight is identified as the major source of increased energy consumption in the galvanization process. The over-processing is minimized by reducing dipping time up to 3 minutes from 5 minutes. A significant reduction of 39.28% in LPG consumption is identified after reducing dipping time to 3 minutes. The combined uses of Six Sigma's DMAIC & DOE approach help to improve the galvanization process of the industry.*

Key Words: Energy consumption, Design of Experiments, DMAIC, Six Sigma, hot-dip galvanization.

1. INTRODUCTION

The world's energy demand increases continuously day by day but the production of energy sources is not sufficient to fulfil this demand especially in developing countries like India. Also, the sources of non-renewable energy sources such as natural gases, liquefied petroleum gas (LPG) & other petroleum products, etc. are limited. The manufacturing industries are key consumers of the non-renewable energy sources are the key energy inputs for the manufacturing industries such as steels industries, & galvanizing industries. Energy saving in the industries is an opportunity for the developing countries rather than exploiting natural resources to increase the production of energy sources. Concerning energy savings in industries, a case study has been conducted in this paper on a galvanizing industry. The LPG is utilized to melt the solid zinc to keep it in the molten form at the same to maintain the 450°C temperature, which is the standard temperature of a zinc bath for the galvanization process. In the galvanization process, a major amount of energy is consumed by the products themselves [4] which may be due to the over-processing of products & the chemistry of the products. Many possible factors affect the energy utilization in hot-dip galvanization. In this paper, the design of experiments technique has been adopted and implemented by Six Sigma's DMAIC process to identify the principal sources of energy losses & optimize these factors by which the energy consumption can be minimized.

2. LITERATURE REVIEW

This section reviews the various works of literature based on energy efficiency in the galvanization process. Further, also review the kinds of literature based on the utilization of Six Sigma by adopting various techniques of experimental design or Design of Experiments.

2.1 Energy-efficiency in Hot-dip Galvanization

To reduce the gas consumption in the galvanization process, the energy planning method is employed by Valencia et al. (2017) [3]. The authors prepared 4 stage models of the energy management system, energy policy, planning, implementation & verification of energy; to achieve continuous improvement. In this case study 3 energy performance indicator was considered first gas consumption, second time & third on is production level. This study shows 10% energy saving potential and also addressed that this method helps to minimize operational cost & also minimalize greenhouse gas emission.

Energy efficiency in any production system can be obtained by waste minimization & pollution control. In the context of the galvanization process to achieve improvement in energy efficiency & reduction in an overall emission of exhaust, some parameters are considered & system levels have been changed by Szymczyk & Kluczek (2017) [2]. Authors replaced electric heaters used a system of cogeneration in place of this. They claim that for energy saving & improvement the cogeneration is extremely effective & obtained a 23% reduction in energy requirement. The authors also addressed some new technologies for energy improvement such as flameless combustion.

Sundaramoorthy et al. (2016) [6] established the enhanced galvanizing energy profiler decision support system (E-GEPDSS) by using heat balance analysis for the identification of specific energy consumption in galvanizing lines & investigated that less than 50% of heat is absorbed by the product only, in an annealing furnace. It is also noticed that in annealing maximum amount of energy is lost due to the melting of zinc ingot and maintaining the constant zinc pot temperature. The authors also used heat balance analysis for energy consumption reduction, to improve the performance of energy systems & gain competitive advantages.

The Galvanizing Energy Profiler and Decision Support System (GEPDSS) is also utilized in a continuous galvanizing line to obtain energy efficiency. The energy consumption optimization has been done for production time and downtime by Bhadra et al. (2013) [6]. The author suggested that natural gas equipment should be prioritized more, to achieve energy efficiency & also achieved some important savings of energy.

To describe the furnace efficiency by lowering the energy consumption, Blakey & Beck (2004) [5] presented a dimensionless equation that can be used for any type of fuel & any size of furnace. The major aim of this is to increase the burner turndown & minimize the production rate dependencies. The thermal efficiency is defined by SECdemand and SECsupply (Specific energy consumption for demand & supply).

2.2 Six Sigma implementation for energy savings

Kaushik & Khanduja (2009) [15] utilized the DMAIC (define-measure-analyze-improve-control) methodology in a thermal power plant to minimalize the exploitation of de-mineralized water in the process of water steamed cycle. The authors utilized various tools in different phases of DMAIC such as process map, histogram, bar graph, and fishbone diagram & process capability analysis to lessen the water consumption. The authors reported that after the Six Sigma implementation the INR 321.84 lakhs can be reduced per annum.

Besseris (2011) [7] adopted Six Sigma's DMAIC approach by utilizing the orthogonal design developed by Taguchi for fuel consumption optimization in maritime operation. The author implemented the lean & green Six Sigma approach by considering 3 parameters fuel consumption, the temperature of exhaust & speed of vessel & found lean with green Six Sigma adoption improve the process of maritime operation.

Falcón et al. (2012) [8] implemented DMAIC methodology in a naphtha reforming industry to achieve energy efficiency in the distillations units of this industry. The author utilized various tools in DMAIC phases, such as in define phase SIPOC & capacity analysis, in measure phase Pareto diagram, in analyze phase regression & solver tool & in improve phase capacity analysis has been utilized. They claimed the improvement in energy efficiency & 150,000€/year savings estimated after the Six Sigma implementation.

Lee et al. (2014) [16] proposed planning of energy management by employing Six Sigma in manufacturing industries. The authors prepared an energy audit, analyze that, and developed an energy improvement & maintenance action plan. They found that Six Sigma is an advantageous tool for energy planning & savings.

Singh & Bakshi (2014) [14] focused on energy (power) crises with increased demand in the context of India and applied the Six Sigma technique in backup power systems. The authors performed the null hypothesis & ANOVA. The authors found significant savings in the cost after improvement.

Baswaraj et al. (2015) [9] implemented the DMAIC approach in a secondary steel industry & reported that Six Sigma not only enhance energy efficiency but also waste & emission of greenhouse gases.

Kaushik et al. (2016) [1] implemented using Design of Experiments in improve phase in the context of the bicycle manufacturing industry. The factorial model of experimental design has been adopted by the authors for the pin length. They investigated the pin length is affected by griding mechanism & feed device. The authors found a reduction in defects up to 0.1 parts per million and by which an 11% reduction in electricity has been reported.

Feng et al. (2018) [13] uses the Six Sigma methodology and adopted SIPOC, fishbone diagram & failure mode effect analysis (FMEA) for energy saving in the assembly process of lamp & reported the reduction in the rejection & rework rate with productivity improvement.

Verma et al. (2021) [12] developed a lean energy Six Sigma value stream mapping (LESSVSM) by utilizing the Six Sigma DMAIC approach. The entropy principle is adopted for energy consumption analysis. The authors investigated the LESSVSM helps to identify the rejection & rework rate and also helps to minimize energy consumption due to rejection & rework.

The utilization of Six Sigma & DOE is limited and less consistent in the field of galvanization for energy consumption reduction. Hence, the integrated approach of Six Sigma & DOE is applied in a galvanizing industry for energy consumption optimization in this paper.

3. METHODOLOGY

A case study has been conducted to optimize the energy consumption in the hot-dip galvanizing industry. Six Sigma's DMAIC (Define-Measure-Analyze-Improve-control) methodology is utilized with a single replicate full factorial model of the design of experiment. The Energy consumption optimization is done by following the 5 steps of DMAIC.

3.1 Define Phase

Liquefied Petroleum Gas (LPG) is used for heating the galvanizing furnace generally called zinc bath to keep the zinc in liquid form and maintain the temperature of zinc bath up to 450℃. The consumption of LPG depends upon the 3 factors that are discussed below.

1. Over-processing of the product
2. Rejection and Rework of the product
3. The thickness & weight of the products load

The objective of the case study is stated by the "Defined phase" which is to identify the major source of energy consumption out of these 3 factors and optimize the energy consumption.

3.2 Measure Phase

To measure the LPG consumption the 2^3 factorial single replicate experimental design or Design of Experiments (DOE) is adopted. The first step of the DOE is the factor & level selection. The factors are already mentioned in the Define phase & corresponding levels are mentioned in table 1 below.

Table -1 : Factors & Levels

S. No.	Factors	Level of factors	
		Low level (0)	High level (1)
1	Over-processing (A)	Dipping time equal to 3 minutes	Dipping time equal to 5 minute
2	Rejection & Rework (B)	No Rejection/Rework	Rejection & Rework occurred
3	Thickness & Weight of product (C)	Thickness < 10 mm Weight < 3500 kg	Thickness > 10 mm Weight > 3500 kg

The level of over-processing is defined by low and high levels. When the dipping time is equal to 5 minutes then considered as high level whereas when dipping time is 3 minutes are considered as low level. Similarly according to the thickness & weight of the products loaded in a rack is considered as the levels. When the loaded rack consists of the product having greater than 10 mm cross-sectional thickness & weight of rack is greater than 3500 kg then the considered as high load level & when the cross-sectional thickness is less than 10 mm & weight of rack is less 3500 kg then the considered as low load level. The level of rejection and rework is defined by no rejection/rework & occurrence of rejection/rework part. The no rejection/rework is considered as low level & the occurrence of rejection/rework is considered as high level.

The data collection is the most essential part of the Measure phase. The LPG consumption per day in kg/day has been collected based on 3 factors and their different levels..

3.3 Analyze Phase

The design matrix has been prepared in the Analyze phase and shown in table 2 for a single replicate 2^3 factorial DOE. The analysis of the factorial DOE has been conducted in this phase also. To analyze the DOE model the calculation of factors effects is required based on which the model analysis will be performed. The factor & interaction effects are calculated by the contract by the following formula given by [11]. The calculated contrasts and effects are given in table 3.

The analysis of single replicate is done in many ways such as normal probability plots, pooling higher-order interaction, and by "Lenth's" method, etc. In this case study, the analysis has been done by plotting a normal probability plot for factor & interaction effects as well as utilizing "Lenth's".

Table -2: 2^3 factorial Design Matrix for LPG consumption

Factor A	Factor B	Factor C	LPG consumption (kg/day)	Designation of treatments
0	0	0	475	[1]
1	0	0	1330	a
0	1	0	570	b
1	1	0	1045	ab
0	0	1	1520	c
1	0	1	2755	ac
0	1	1	2280	bc
1	1	1	2850	abc

Table -3 : Factor & interaction effects

Factor	Contrast	Effects
A	3135	783.75
B	665	166.25
C	5985	1496.25
AB	-1045	-261.25
AC	475	118.75
BC	1045	261.25
ABC	-285	-71.25

3.3.1 Analysis by Normal Probability Plot

The normal probability plot for factor & interaction effects is given in figure 1 below.

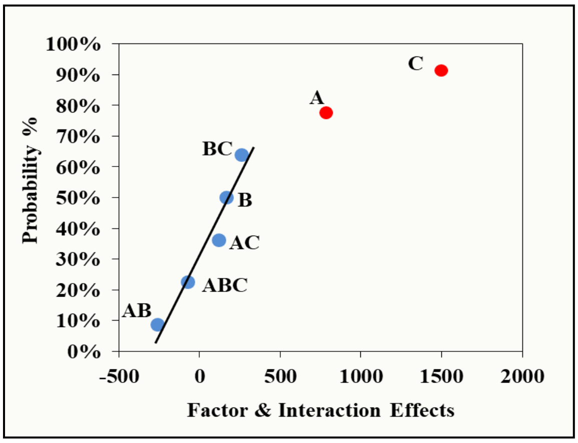

Fig -1 : Normal probability Plot for factor & interaction effects

From figure 1 it can be viewed that other than A & C all factor and interaction effects lie approximately on the straight line whereas the factor A & C both are outliers and do not lie on the straight line. This states that factor A & C has a greater & significant effect on an increase in LPG consumption & to minimize the consumption these two factors are considered. This result is cross-checked by adopting Lenth's method in the next section.

3.3.2 Analysis by Lenth's Method

Lenth's analysis has been performed by estimating lengths parameters for the significance level (α) equal to 0.1 or 10 % significance level. The Lenth's parameter consists of s0, pseudo standard error (PSE) & margin of error (ME) [11]. The estimated Lenth's parameters values are given in table 4.

Table -4 : Estimated Lenth's Parameters

Lenth's Parameters	Formula's	Estimated values	
s_0	1.5 × median of the absolute value of all 7 effects	1.5 × |166.25|	249.375
PSE	1.5 × median of the absolute value of effects < $2.5s_0$	1.5 × |118.75|	178.125
ME	$t_{\alpha/2,\,d}$ × PSE	2.73 × 178.125	486.28

According to Lenth's analysis, the factor or interaction having effect values greater than the margin of error (ME) are significant and have a noteworthy effect on the response. In this case factor, A & C both have effect values 783.75 & 1496.25 which is greater than the margin of error (ME) i.e. 486.28. To visualize the result of Lenth's analysis the Pareto graph is presented in figure 2.

From fig 2, it is visible that only factors A & C are significant factors that have a significant impact on the increase in LPG consumption. Considering the factor A & C the model refinement & checking for model adequacy has been performed in Improve phase & improvement suggestions has been made.

3.4 Improve Phase

From Analyze phase it is investigated that the over-processing (factor A) and thickness & weight of the products are the major sources of LPG consumption in the hot-dip galvanization process. The refinement of model & adequacy is performed by regression analysis & residual plots. The regression equation for the LPG consumption (kg/day) by considering factors A & C is given in equation 1. The LPG consumption in kg/day is denoted by CLPG & the x & y are coded variables.

$$C_{LPG} = 1603.125 + 391.875\,x + 748.125y \qquad \text{..............} (1)$$

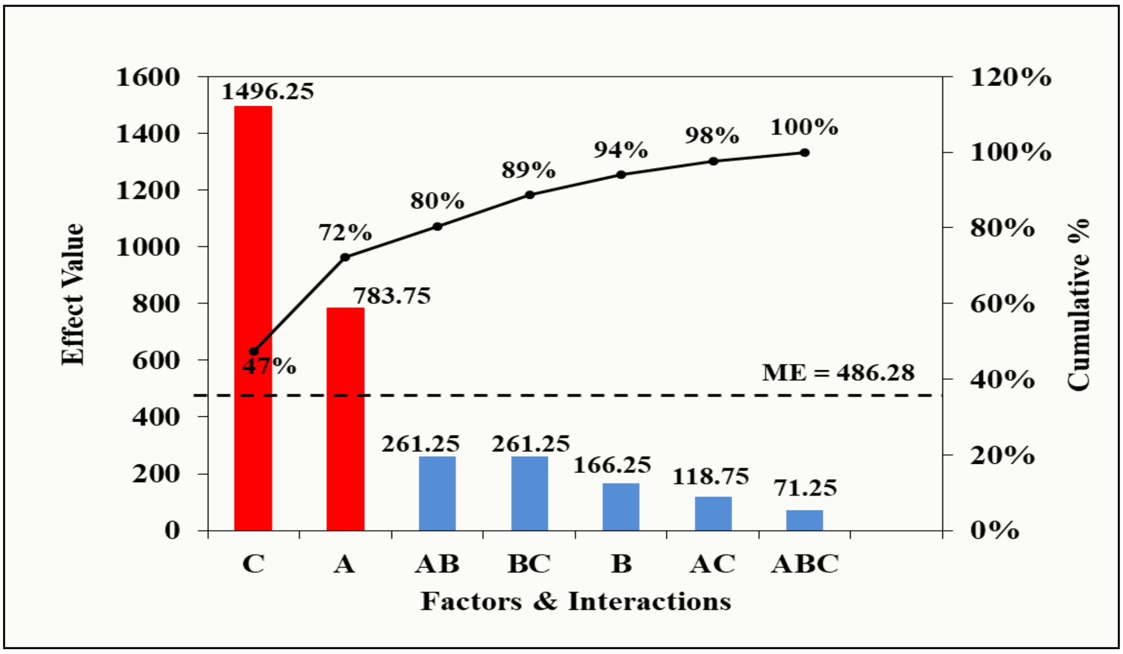

Fig -2 : Pareto graph for LPG consumption factor & interaction effects

In equation (1), the x & y can be calculated from [11]. When factor A is at a high level the x will be 1 & when at low-level x will be -1. Similarly, when factor C is at a high level y will be 1 & when at a low-level y will be -1. By substituting the values of x & y in equation (1) the predicted LPG consumption has been calculated. The predicted LPG consumption kg/day and residuals were obtained by subtracting predicted values from actual LPG consumption data. The all these calculated values and residuals are mentioned in table 5.

Table -5: Residuals of LPG consumption (kg/day)

S. No.	Actual LPG consumption	Predicted LPG consumption	Residuals
1	475	463.125	11.875
2	570	463.125	106.875
3	1330	1246.875	83.125
4	1045	1246.875	-201.875
5	1520	1959.375	-439.375
6	2280	1959.375	320.625
7	2755	2743.125	11.875
8	2850	2743.125	106.875

The normal probability and residual v/s predicted plot is plotted for the LPG consumption DOE model by using residuals given in table 5. Both normal probability & residual v/s predicted plot is given in figure 3 (a) & (b). Figure 3 (a) & (b) both are satisfactory and validated the single replicate full factorial DOE for LPG consumption.

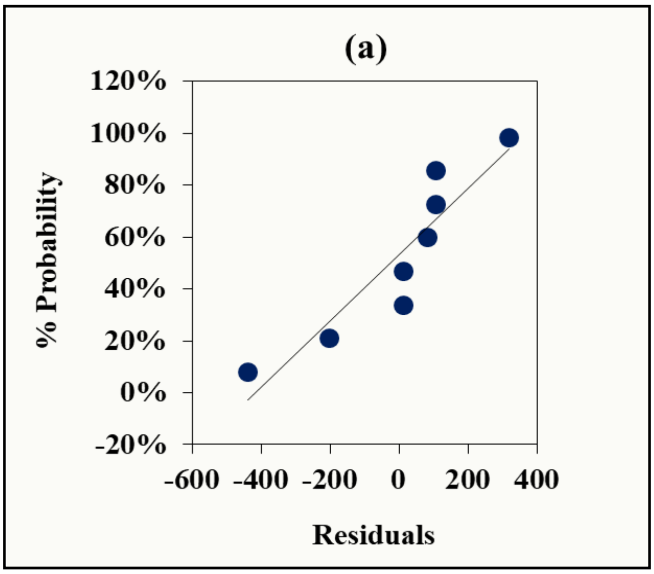

Fig -3(a) : Normal Probability Plot

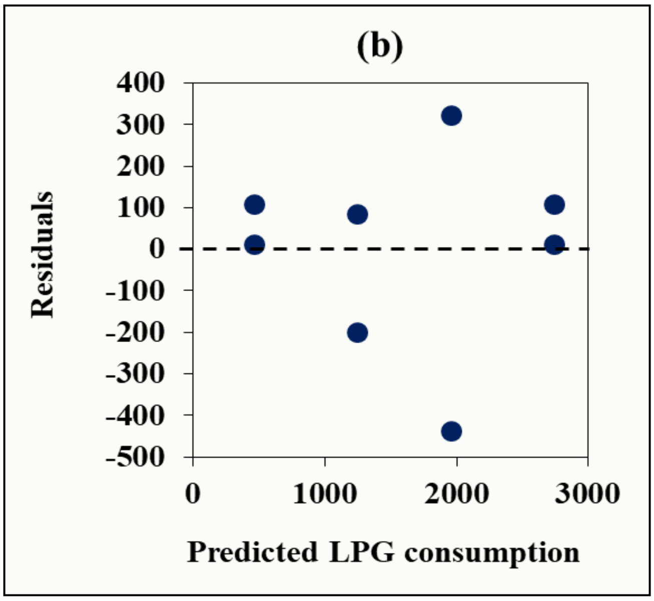

Fig -3(b) : Residual v/s Predicted plot for LPG consumption DOE

Considering the factor A & B main effect plot has been prepared in figure 4 (a) & (b) respectively. From figure 4 (a) & (b) it can be viewed that the highest LPG has been consumed when the thick & weight of the products both are at a high level. After that, the highest amount of LPG is consumed when over-processing has been done in the zinc bath. When both factors A & B are at a low level then the LPG consumption has been reduced. From both factors, A & C, the factor C i.e. the high cross-sectional thickness & weight, which is the product's attributes and depends on customer's demand, thereby cannot be overcome. Hence, only factor “A” i.e. over-processing can be reduced by controlling the dipping time.

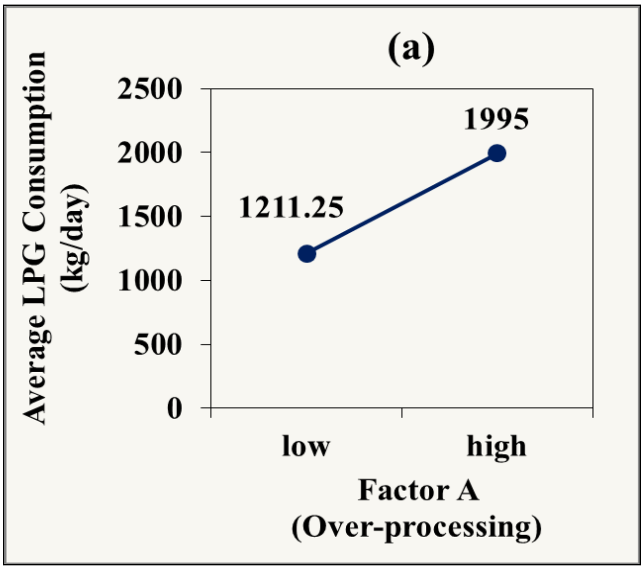

Fig -4(a) : Main effect plot of factor A on LPG consumption

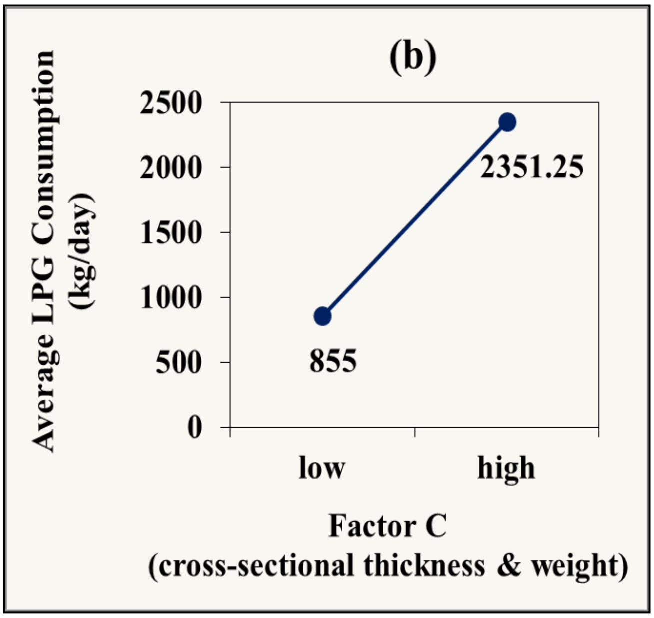

Fig -4(b) : Main effect plot of factor C on LPG consumption

3.5 Control Phase

The over-processing i.e. dipping time is increased due to several reasons such as carelessness of workers & supervisors, no empty place in quenching bath, and oil & grease present on products that are not removed completely by pre-galvanizing treatment, etc. The proper care and attention should be given by the supervisors and workers to control the dipping time. The impurities such as oil, grease, and rust, etc. should be completely removed during pre-galvanizing treatment. By following all these suggestions the over-processing can be reduced in the galvanization process which will result in reduced consumption of LPG.

4. RESULT & DISCUSSION

From the implementation of Six Sigma by integrated approach of single replicate full factorial DOE the following results have been obtained.

- In the Define phase of Six Sigma, the most probable cause of LPG consumption has been identified.
- In the Measure, the DOE's full factorial model has been applied to optimize LPG (energy consumption). The Factors & their level selection, as well as the design matrix, have been prepared with the aid of data collected from galvanizing industry regarding LPG utilization kg/day.
- From Lenth's analysis, this DOE model has been analyzed and investigated that factor A (over-processing) & factor C (load due to cross-sectional thickness & weight of the product) are the most significant factors that increase consumption of LPG.
- The model refinement & model adequacy checking have been done in the Improvement phase which significantly validated the DOE model for 0.1 or 10% significance level and supports the result of Analyse phase.
- The over-processing & load on the zinc bath due to high cross-sectional products are the major source of excessive LPG exploitation and in the Improvement phase, some suggestions have been made to overcome over-processing by reducing dipping time 5 minutes to 3 minutes. The reduction in LPG consumption by over-processing minimization is shown in figure 5. The total 39.28% reduction in LPG consumption has been obtained after improvement or by setting dipping time up to 3 minutes.

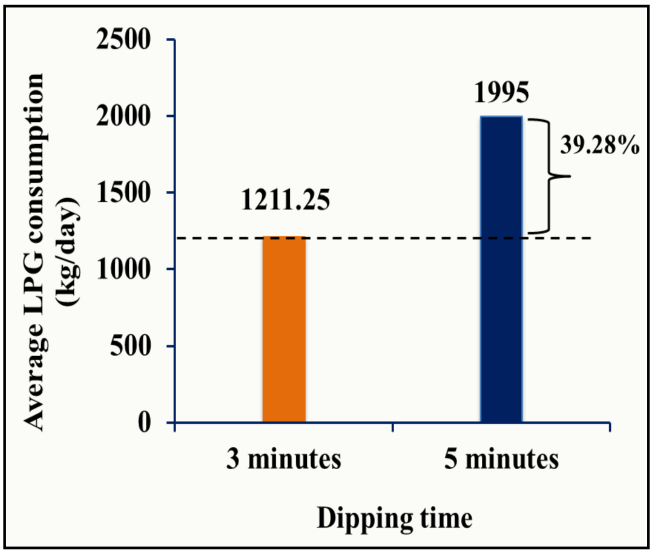

Fig -5 : Reduction in LPG consumption after Improvement

5. CONCLUSION

The energy consumption optimization in the hot-dip galvanization process has been carried out in this case study. Six Sigma's DMAIC methodology has been implemented by utilizing the Six Sigma tool Design of experiments. The Full factorial model of DOE with a single replicate has been adopted for LPG (energy) consumption optimization. The Length's analyzed the two major energy-consuming factors over-processing & excess load due to the high cross-sectional thickness and weight of the products. The regression analysis, normal probability, and residual plots are validated the statistical significance of the outcomes. It is investigated that to reduce consumption of LPG the minimization of over-processing is required. To minimalize over-processing the 3 minutes of dipping time has been set. By setting 3 minutes of dipping time the 39.28% reduction in LPG consumption has been obtained as compared to 5 minutes of dipping time. The implementation of Six Sigma by DOE not only recognizes the root cause of the problem but also optimizes the problem and provides a suitable solution. In this case study, the DOE integrated Six Sigma methodology helps the galvanizing industry to become energy efficient with a sustainable production process.

REFERENCES

[1] P. Kaushik, K. Mittal, and P. Rana, "Energy paybacks of six-sigma: A case study of manufacturing industry in India," Manag. Sci. Lett., vol. 6, pp. 691–700, 2016, doi: 10.5267/j.msl.2016.10.001.

[2] J. Szymczyk and A. Kluczek, "Increasing the energy efficiency of a hot-dip galvanizing plant and reducing its environmental impact," J. Power Technol., vol. 97, no. 5, pp. 349–358, 2017.

[3] G. Valencia, E. Ramos, and L. Meriño, "Energy planning for gas consumption reduction in a hot dip galvanizing plant," Chem. Eng. Trans., vol. 57, pp. 697–702, 2017, doi: 10.3303/CET1757117.

[4] S. Sundaramoorthy, Q. Phuong, B. Gopalakrishnan, and H. H. Latif, "Heat Balance Analysis of Annealing Furnaces and Zinc Pot in Continuous Hot Dip Galvanizing Lines," Energy Eng. J. Assoc. Energy Eng., vol. 113, no. 2, pp. 12–47, 2016, doi: 10.1080/01998595.2016.11668651.

[5] S. G. Blakey and S. B. M. Beck, "Energy consumption and capacity utilization of galvanizing furnaces," Proc. Inst. Mech. Eng. Part E J. Process Mech. Eng., vol. 218, no. 4, pp. 251–259, 2004, doi: 10.1243/0954408042466927.

[6] S. Bhadra, B. Gopalakrishnan, and S. Chaudhari, "Energy efficiency in continuous galvanizing lines," Proc. 2013 Int. Renew. Sustain. Energy Conf. IRSEC 2013, pp. 361–366, 2013, doi: 10.1109/IRSEC.2013.6529723.

[7] G. J. Besseris, "Applying the DOE toolkit on a lean-and-green Six Sigma maritime-operation improvement project," Int. J. Lean Six Sigma, vol. 2, no. 3, pp. 270–284, 2011, doi: 10.1108/20401461111157213.

[8] R. G. Falcón, D. V. Alonso, L. M. G. Fernández, and L. Pérez-Lombard, "Improving energy efficiency in a naphtha reforming plant using Six Sigma methodology," Fuel Process. Technol., vol. 103, pp. 110–116, 2012, doi: 10.1016/j.fuproc.2011.07.010.

[9] A. B. S, M. S. Rao, and A. S. Kumarr, "International Journal of Modern Trends in Engineering and Research Energy Consumption Optimization for Secondary Steel by Six Sigma (DMAIC)," no. 2349, pp. 2–4, 2015.

[10] W. Cai et al., "Promoting sustainability of manufacturing industry through the lean energy-saving and emission-reduction strategy," Sci. Total Environ., vol. 665, pp. 23–32, 2019, doi: 10.1016/j.scitotenv.2019.02.069.

[11] D. C. Montgomery, "Design and Analysis of Experiments Eighth Edition,". John Wiley & Sons Inc. 2017.

[12] N. Verma, V. Sharma, and M. A. Badar, "Entropy-Based Lean, Energy and Six Sigma Approach to Achieve Sustainability in Manufacturing System," Arab. J. Sci. Eng., no. June, 2021, doi: 10.1007/s13369-021-05826-x.

[13] T. Feng, Y. Zhang, X. Wang, and Y. Li, "Application of lean six sigma in energy saving lamp assembly process," J. Phys. Conf. Ser., vol. 1053, no. 1, 2018, doi: 10.1088/1742-6596/1053/1/012129.

[14] B. J. Singh and Y. Bakshi, "Optimizing backup power systems through six sigma: An Indian case study of diesel genset," Int. J. Lean Six Sigma, vol. 5, no. 2, pp. 168–192, 2014, doi: 10.1108/IJLSS-09-2012-0008.

[15] P. Kaushik and D. Khanduja, "Application of six sigma DMAIC methodology in thermal power plants: A case study," Total Qual. Manag. Bus. Excell., vol. 20, no. 2, pp. 197–207, 2009, doi: 10.1080/14783360802622995.

[16] J. Lee, K. Yuvamitra, K. Guiberteau, and T. A. Kozman, "Six-sigma approach to energy management planning," Strateg. Plan. Energy Environ., vol. 33, no. 3, pp. 23–40, 2014, doi: 10.1080/10485236.2014.10781519.

BIOGRAPHIES

Niharika Choubey, M. Tech Student, Department of Mechanical Engineering, SSIPMT Raipur, (C.G.)

Neha Verma, Assistant Professor Department of Mechanical Engineering, SSIPMT, Raipur, (C.G.)