Using Design of experiment &Steepest Ascent Methodologies to Improve Air Leak Testing in Engine Block Manufacturing System

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Abstract

Process and product development are crucial objectives in most manufacturing companies. Optimal operation conditions setup plays a critical role in these objectives. Also, total efficiency and effectiveness with which the development process is performed are often a key role in organizational success. Design of experiment (DOE) represent very powerful tool for process improvement. This technique is mostly used by large and manufacturing automotive companies. Presented paper is focused on use of DOE in engine block manufacturing system, such study has several purposes. Firstly, it provides example of successfully implemented low cost design of experiment studies. Secondly, detailed description of process improvement effort based on steepest ascent methodology. Moreover, performed experiment identifies key factors, which influence the efficiency of the system. Results show that the pressure of vacuum chamber is the most significant factor on the system Based on the final model, to maximize the productivity, the factors should be placed on the optimal set up of all-natural variables, especially pressure of vacuum chamber, which is 94 kPa instead of 99 kPa as well as soap temperature, which is 97.98 ºF instead of 104 ºF . Also results showed the system became more robust due to eliminating repeated air leak tests and that led to increase the throughput and enhance the entire efficiency of the system.

Keywords

DOE, FMS, Steepest Ascent, Aluminum Engine Blocks

1. Introduction

Most manufacturing companies suffered from, bad performance measure, serious quality issues with high cost, variation in process, process bottlenecks, low efficiency and very low level of profitability. On the other hand, all these companies, especially automotive companies are living under severe pressure due to competitive environment. New technology can serve as a driver of change for any organization or businesses. In engineering and manufacturing disciplines, knowledge about product and process development is often derived from experience and experimentation. Experiments can bring a lot of opportunities and unexpected very good ideas and results. A strategy of experimentation that could address the above challenges is needed in order to stay ahead of competition. Design of experiments (DOE) is one of an alternative answer to the above challenges.

Design of experiments (DOE) is one of the most process development tools that can be used for various investigations such as finding the significant factors in a process, the effect of each factor on the system, screening, modeling and optimization. Design of Experiment is a powerful methodology that studies the effect of several process parameters affecting the response of a process or product, Johnson et al. (2012). Ouyang et al. (2017), mentioned DoE plays a crucial role in problem solving in automotive industry. Evans at el. (2011), Antony et al. (2011) and Geiges et al. (2015) mentioned that, even though DOE techniques are not new tools, but its application has expended rapidly over the manufacturing areas including system improvement, quality of product and optimization in the past two decades. Sinha (2011) stated that DoE is recognized as an approach for quality improvement through variation reduction as well as process enhancement. Recent studies showed DOE is used as improvement tool for large organization to support their operation and system improvements by Chompu-inwai et al. (2014). As a result, the methodological tools of DOE have high ability in minimizing time, effort and cost.

1.1 Case Study

The first step is already done in this research which is simulation optimization studies. It's already applied on engine block manufacturing system with initial conditions to make sure that we are achieving the target. The throughput has been achieved even though we identified some problems in system. In this paper the problems are, since the aim of the flashing and washing process in engine block manufacturing system is to keep the parts clean and dry before the parts moved out to the leak test. The efficiency of these processes relies on the soap temperature, the pressure of the vacuum chamber, inside temperature, and the inside humidity. When the parts are still not clean enough and /or are wet during the leak test, this leads to a negative impact on the leak test data and significant delays due to repeated leak tests because of porosity, excessive flash and dirty washing processes. Disturbance in the flow of a production line is a result of all those delays leading to bottlenecks in the system. Furthermore, these reasons will have a potential negative impact on throughput and overall efficiency of the system. The objectives of this paper are to improve the process and entire system by eliminating the bottlenecks in washing, flashing and leak testing processes. Also figure out which is the most significant factor that have potential effect on system. As well as find out new setup for the optimal operation conditions by finding a new region for improvement that may increase the throughput and improve aver all system efficiency by using experimental design and steepest ascent or descent method.

2.0 Design of Experiment

Two level factorial designs are commonly used in experiments involving several factors where it is essential to investigate the combined impacts of the factors and their interactions on response variables. The number of experiments can be calculated by using 2^k where k is the number of factors. These designs are usually called 2^k factorial design. The reasons why factorial designs are very important in response surface work is to identify the most important process and system variables. Factorial design is also used to fit a first order response surface model and to generate the factor-effect estimates required to implement the steepest ascent and/or steepest decent method. Table 1a shows sixteen experiments within the coded matrix design and Table 1b shows design levels.

This model investigated the influence of following four factors on the quality of the part (dimension) and on the testing data (cleanliness factor).

- Incoming part temperature (A)
- Cooling time (B)
- Soap temperature (C)
- Pressure of vacuum chamber (D)

Table 1a. Two levels and four factors coded design

Run Number	**A Incoming part temperature (^{o}F)**	**B Cooling time (sec)**	**C Soap temperature (^{o}F)**	**D Pressure of vacuum chamber (kPa)**	**Treatment Combination**	**Cleanliness**
1	-	-	-	-	1	
2	+	-	-	-	a	
3	-	+	-	-	b	
4	+	+	-	-	a b	
5	-	-	+	-	c	
6	+	-	+	-	a c	
7	-	+	+	-	b c	
8	+	+	+	-	a b c	
9	-	-	-	+	a	
10	+	-	-	+	a d	
11	-	+	-	+	b d	
12	+	+	-	+	a b d	
13	-	-	+	+	c d	
14	+	-	+	+	a c d	
15	-	+	+	+	b c d	
16	+	+	+	+	a b c d	

2.1 Experimental Procedures

Performing a screening analysis is a very essential approach to screen out all factors that have severe impact on a system. A sediment test is used to measure the part cleanliness factor by weighing the part before and after the washing processes. Specifications indicated that less than 300 mg of undesirable particles are accepted. Similarly, for the vacuum chamber pressure, standards require that the crank case cavity be not less than 25 cc/min at 50 kPa, otherwise a false reading result.

2.2 Design Setup

Depending on the thermal mapping analysis and sediment test, Table (2) shows how the four factors and their interactions within 2 levels affected cleanliness factor.

Table 2**.** Design matrix of clealiness response

Run Factor	**A Part incoming temperature (^{0}F)**	**B Cooling time (sec)**	**C Soap temperature (^{0} F)**	**D Pressure of vacuum chamber (kPa)**	**Cleanliness**
1	75	51	80	87	388
2	108	51	80	87	356
3	75	59	80	87	382
4	108	59	80	87	361
5	75	51	104	87	336
6	108	51	104	87	324
7	75	59	104	87	331
8	108	59	104	87	298
9	75	51	80	99	262
10	108	51	80	99	228
11	75	59	80	99	357
12	108	59	80	99	231
13	75	51	104	99	188
14	108	51	104	99	124
15	75	59	104	99	173
16	108	59	104	99	119

Table 1b**.** Design levels

	Unit design	
Factors	-1	+1
A: Incoming part temperature (ºF)	72	108
B: Cooling time (sec)	51	59
C: Soap temperature (ºF)	80	104
D: Pressure of vacuum chamber (kPa)	87	99

3.0 DOE Results

On the right side of Figure 1, the points in blue are basically in a straight line. They follow a normal distribution. In other words, the insignificant deviation due to their expectation or percentile is proportionate to the size of the effect. The ones in red (A, C, D, and CD) are outliers and stand away from the ones in the side, indicating that they are not just random noise but must be significant.

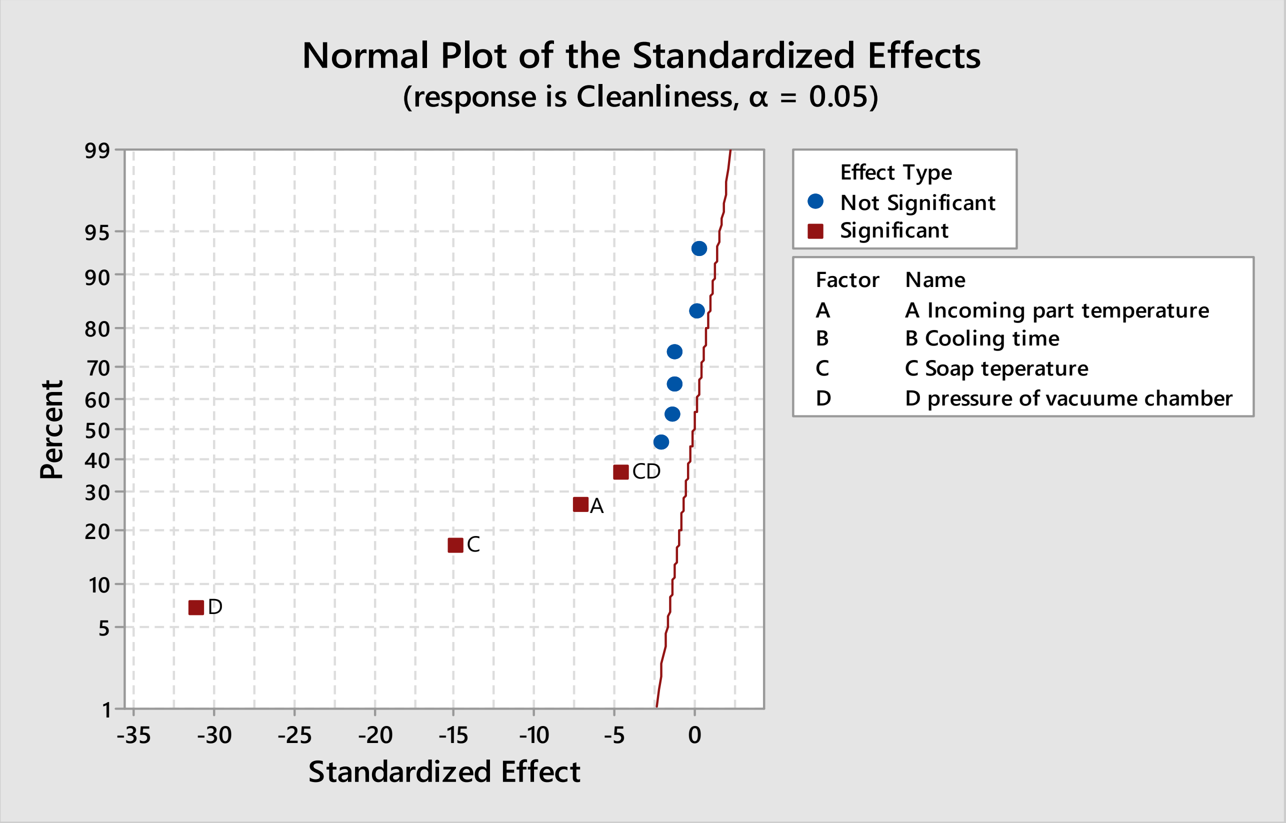

Figure 1**.** Normal plot of the effect of cleanliness

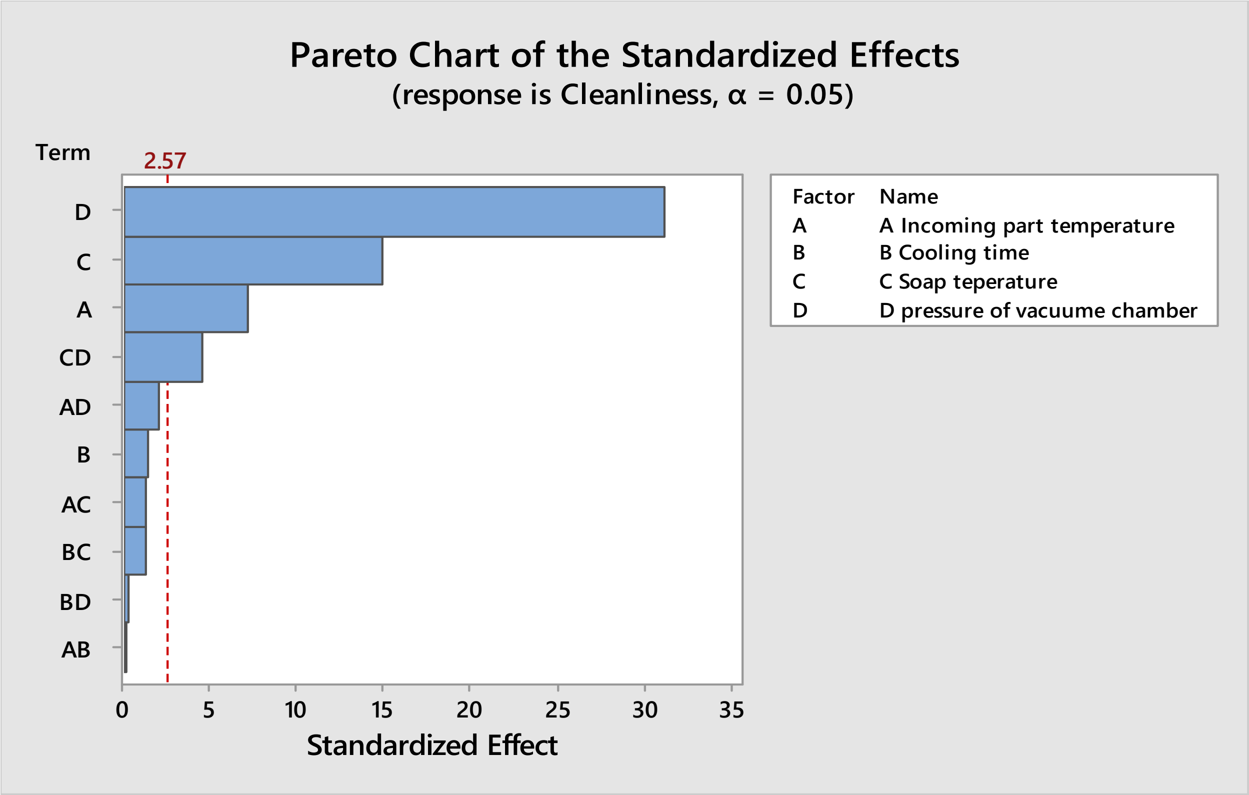

Figure 2. Pareto chart of the effect of cleanliness

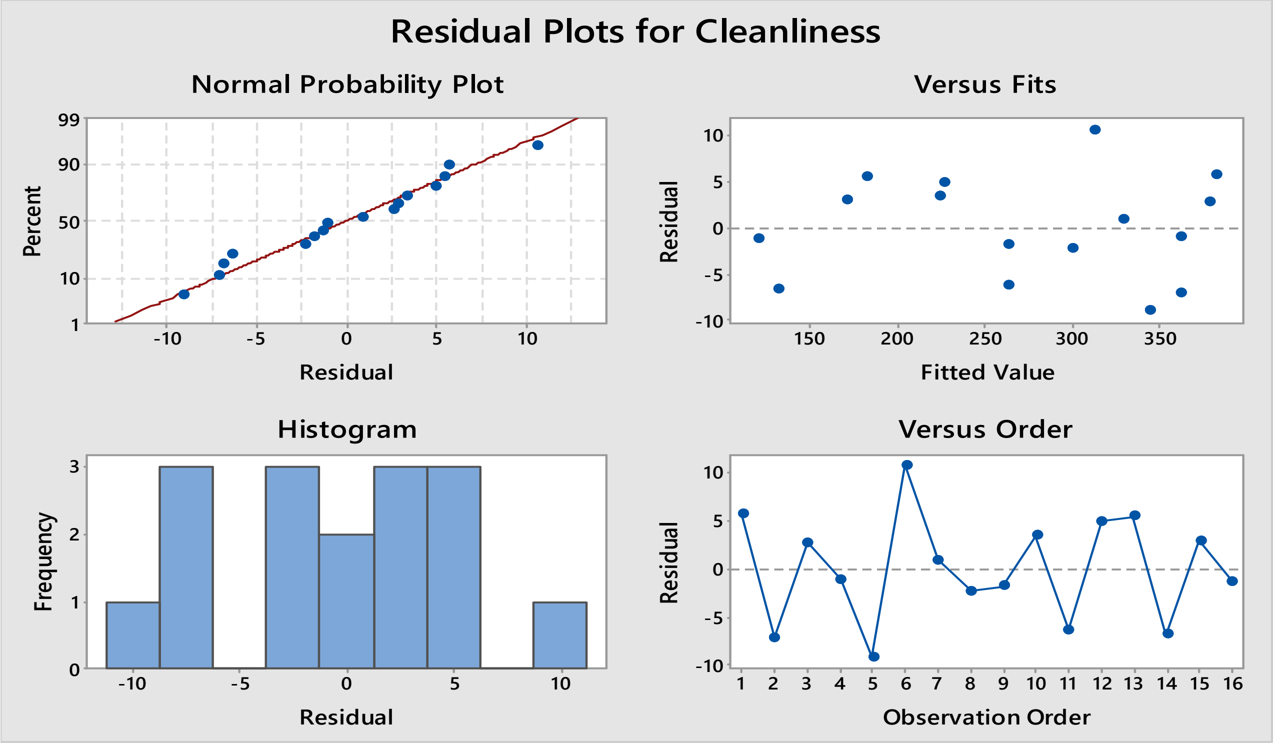

Figure 3. Residual plots for cleanliness

Figure 2 is another Pareto chart showing what is most important by looking at the size of the impacts and plots the effect size on a horizontal axis ranked from largest to smallest impact. Thus, the pressure of vacuum chamber and soap temperature have the largest effects on the system.

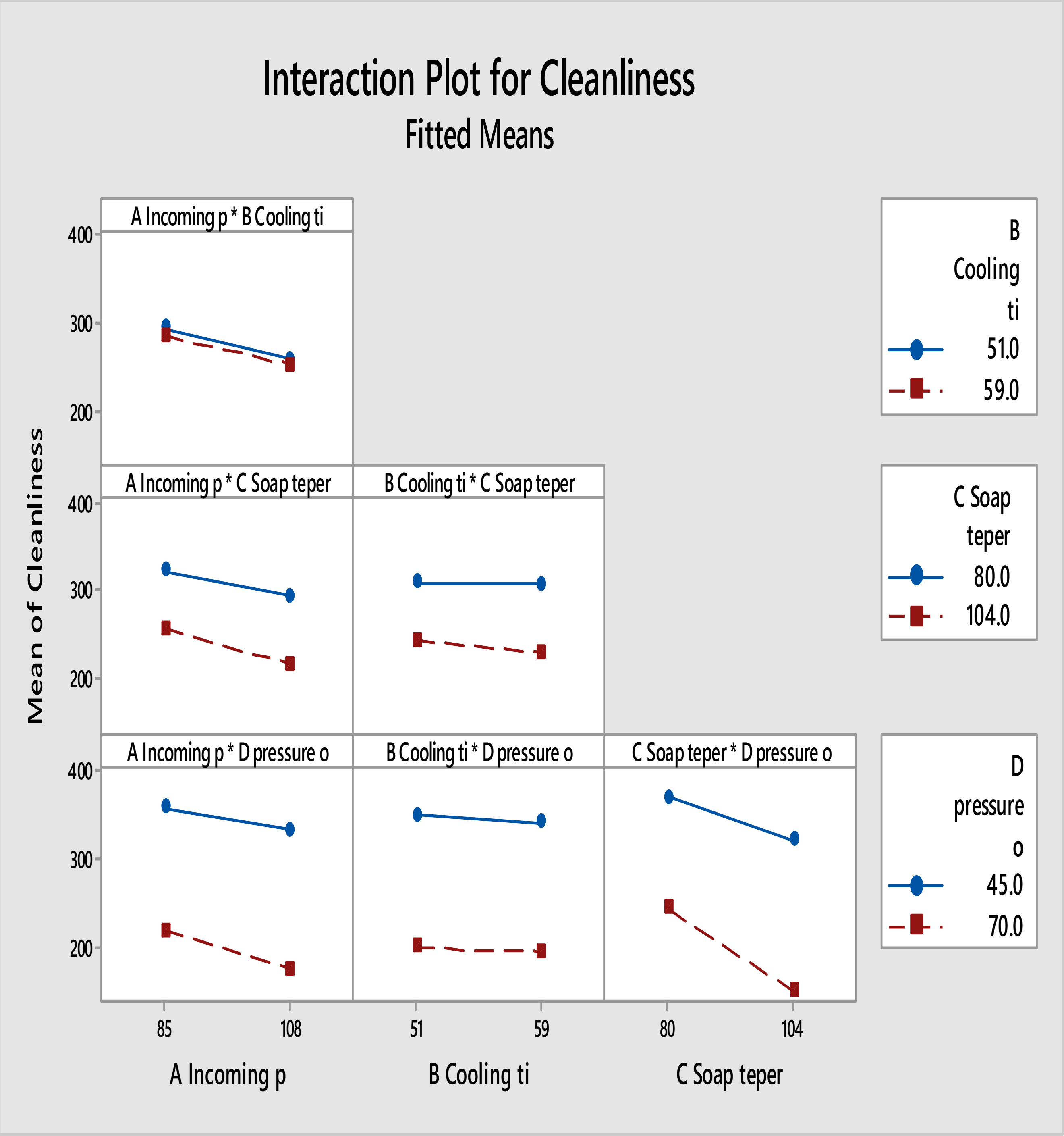

Figure 4. Interaction plot for cleanliness

Checking residuals using Minitab's four-in-one plot is shown in Figure 3. By visually checking the residuals, it is clear that there are not any great deviations in the normal probability plot of the residuals. There's nothing in this figure that is very alarming and it looks acceptable.

Figure 4 shows interaction effects that are not significant because of most of the lines are parallel. However, AB combinations indicate that medium interaction exists.

3.1 Steepest Ascent Method

Steepest ascent is a method whereby the experimenter proceeds sequentially along the path of steepest ascent, that is, along the path of maximum increase in the predicted response.
Equation 1 represents the linear regression model as it relates to predicted cleanliness to the design variables in coded design units. It appears that movement to a region with higher pressure in the vacuum chamber and soap temperature will help to increase the response. In addition, a slight increase in incoming part temperature may be beneficial.

$\text{Cleanliness} = 1080.9 + 1.5\,A + 0.84B + 2.979C + 5.97\,D$……………….……………… (1)

From Equation 11, D is selected as the variable to define the step size (note that D is one of the two largest regression coefficients). Let $\Delta D = b4 / b4 = 5.97 / 5.97 = 1$.

Then from the step size equation

$\Delta A = b1 / b4 = 1.5 / 5.97 = 0.2512$

$\Delta B = b2 / b4 = 0.84 / 5.97 = 0.14$

$\Delta C = b3 / b4 = 2.979 / 5.97 = 0.4989$

The corresponding change in terms of the natural units are:

Δ Incoming part temperature = (0.2512) * ((108- 75) / 2)) = 4.14

Δ Cooling time = (0.14) * ((59-51) / 2)) = 0.56

Δ Soap temperature = (0.4989) * ((104 - 80) / 2)) = 5.98

Table 3**.** Path of steepest ascent

	Coded Variables				**Natural Variables**			
Factor	A	B	C	D	°F	Sec	°F	kPa
Base	0	0	0	0	91.5	55	92	93
Δ	0.2512	0.14	0.4989	1	4.14	0.56	5.98	1
Base+1	0.2512	0.14	0.4989	1	95.64	55.56	97.98	94
Base+2Δ	0.524	0.28	0.9978	2	99.78	56.12	103.96	95
Base+3Δ	0.7752	0.42	0.1483	3	103.92	56.68	109.94	96

Table 3 shows the path of steepest ascent in terms of both coded design units and natural units. The strategy involves making experimental runs along this path until no improvement in response of cleanliness is observed. Also, Table 19 shows the improvement and optimum data of all natural variables, especially pressure of vacuum chamber, which is 94 kPa instead of 99 kPa as well as soap temperature, which is 97.98 ºF instead of 104 ºF.That leads to:

- Parts being drier and cleaner by improving washing processes
- Elimination of false data problems in leak testing process
- Reduction of repeating tests
- Elimination of bottlenecks in leak testing process
- Reduction in down time and increase in uptime of the system
- Increase in the throughput and efficiency of the system

After re–running the simulation model with final set up (optimal setting), the throughput increased from 1530 to 1549 part per day.

4.0 Conclusion

Engine block manufacturing system suffered from low level of productivity and overall efficiency due to process bottlenecks but still there is a good opportunity for improvement. The system has been affected by four factors which are incoming part temperature, cooling time, soap temperature and pressure of vacuumed chamber. Design of experiments is applied to find out the system response and most significant factor that has sever effect on the system. Steepest ascent method also applied to find out the optimal operation conditions. Results show that the pressure of vacuum chamber is the most significant factor on the system. Also, reaching out a new region which are optimal conditions made significant reduction in down time and repeating air leak testing. Addition to increase in the throughput, efficiency of the system and that lead to make the system more robust and profitable.

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Biographies

Khaleel Al ithawi, Ph.D. is a senior manufacturing engineer in Troy Design and Manufacturing. He received his Ph.D. degree in engineering manufacturing systems from Lawrence Technological University. His research has been in the areas of simulation optimization studies, design of experiment, modeling, process, development and manufacturing. He worked at former Iraqi Army -air force as aeronautical engineer and, later, was instructor in military engineering collage, He taught heat transfer, thermodynamics and engineering analysis. He currently working on prototyping, modeling and manufacturing of new models within automotive industry-North America.

Kingman Yee, Ph.D. is an associate professor and director of the M.S. automotive engineering program in the A. Leon Linton Department of Mechanical, Industrial and Robotics Engineering at Lawrence Technological University. He received his Ph.D. degree in chemical/electrochemical engineering from Wayne State University. His research has been in the areas of electrochemical engineering, corrosion, amorphous semiconductors and manufacturing. He worked at General Motors Research Laboratories and, later, was a consultant in Advance Manufacturing Engineering at Chrysler LLC (low-voltage electric clamps, multi-stage modular vacuum cartridges/generators, and resistance spot welding.) He currently teaches courses in engineering materials, heat transfer, engineering economics and senior capstone projects.

Dr. Abro was born and grew up in Baghdad; his family migrated to the US in the late sixties.
Sabah is an internationally-educated person with a bachelor degree from Baghdad University, a master’s degree from the United Nations institute in the Middle East, a Master’s degree from Britain and a Ph.D. from Belgium. Dr Abro is also certified Master Blackbelt in Six Sigma from Ann Arbor, USA firm.
His education helped him to learn four languages, Arabic, English, French and Chaldean.
Sabah’s family is also international, his wife Ann and him are from Baghdad, their daughter Hadeel was born in Britain, their son Fadi in Belgium, their daughter-in-law Marsha in USA, Mark their son- in- law in Mosul, Iraq and their three grandchildren in Michigan.
Dr. Abro served in Universities in Iraq, Jordan and also as a visiting lecturer in Kuwait and Morocco. He assumed different positions such as faculty, regional consultant, chair of department and acting Dean.
In the USA he taught at WSU, UDM and OCC. He was the Math Program Director of Focus: HOPE where he worked with the curriculum committee of the Greenfield Coalition, an NSF sponsored group. This committee designed a complete paradigm in manufacturing engineering education. Courses were developed and delivered at Focus: HOPE by three university partners.
Sabah joined LTU as an adjunct faculty in 1997, then as a full-time faculty in 2000. He served two departments, Math & Computer Science and Engineering Technology.
As a full time, faculty at LTU, he teaches a variety of classes related to Quality, Probability, Engineering Economic Analysis, Engineering Project Management, advises students, works on curriculum improvement, course development, writes professional papers and presents in conferences. He is the Director of Master’s program in Engineering Technology, advises and teaches courses for Doctorate students and is a member of several Doctorate Committees in the College of Engineering.
His services go beyond his department, where he serves in different Doctoral Committees in other Departments of the College of Engineering
Dr. Abro served as Director of the University Assessment Committee and the Vice Chair of the Engineering Faculty Council.
Winner of 2012 Faculty of the Year Award at Lawrence Technological University.
Nominated for Teaching Excellence and Using Technology in Classroom Awards.
His hobbies are many, but his addictions are to play racquet ball and watch movies, where he has special interest in classical western and action movies.

Dr.Ishtiaq Hussain Works in General Motors Powertrain division. Lead and executed and launched multiple metal cutting CNC machines lines at various sites for various Engine and Transmission components. Six sigma certified international professional, with 21 years of experience in engineering Project Management, Quality Management, and Process Engineering. Published several papers on Minimum Quantity Lubricant (MQL) topics. Expert in data analysis, metal cutting, and Leak test equipment. Adjunct faculty in Lawrence Tech. University Southfield MI.

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