Using Design of Experiment & Steepest Descent Methodologies to Improve Cooling Process in Engine Block Manufacturing System

Khaleel Al ithawi
A. Leon Linton Department of Mechanical Engineering
Lawrence Technological University
Southfield, MI 48075, USA
Kalithawi@ltu.edu

Kingman Yee
A. Leon Linton Department of Mechanical Engineering
Lawrence Technological University
Southfield, MI 48075, USA
Kyee@ltu.edu

Sabah Abro
Engineering Technology Department
Lawrence Technological University
Southfield, MI 48075, USA
Sabro@ltu.edu

M. Ishtiaq Hussain
General Motors Powertrain Pontiac
823 Joslyn Ave Pontiac, Michigan
ishtiaq34@hotmail.com

Abstract
Throughput plays a significant role for most manufacturing companies in order to examine the efficiency. There is an essential need to evaluate the effect of different factors which are increasing productivity, profitability and reducing the cost with high level of quality. On the other hand, especially automotive companies are striving to sustain their competitiveness by improving overall manufacturing systems efficiency. This can be attained by process development and figuring out ways to deal with various problems which have affected the performance of manufacturing systems. Design of experiments (DOE) is one of the most problem-solving tools that can be used for various investigations such as finding the significant factors in a process, the effect of each factor on the outcome, the variance in the process, screening the parameters, and process development. In this paper DOE and steepest decent method have been applied to develop optimization and system improvement model by finding optimal operation setup. Results DOE was conducted to determine which factors have the most sever effect on manufacturing system productivity. Results showed that two factors B (cooling time) and A (incoming part temperature) have the most significant impact 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 cooling time, which is 57 sec instead of 55 sec. Also results showed the system became more robust due to eliminating downtime and bottleneck in cooling process. That led to increase the throughput and enhance the entire efficiency of the system

Keywords
DOE, FMS, Steepest Descent, Aluminum Engine Blocks, System improvement

1. Introduction

In the manufacturing industry, upper management are seeking to find methods in order to eliminate the common problems in manufacturing systems such as bottlenecks and downtimes due to all of these kinds of problems impose extra cost to the companies. Most automotive companies that produce engine blocks suffer from inefficient production lines, resulting in very high total cost. Design of experiment (DOE) is a perfect methodology for problems solving and performance measure as well as product and process development. It is multipurpose technique that can be used in different approaches such as design for comparisons, variable screening, optimization and robust design. Bhuiyan et al. (2011), Pandian et al. (2014), Tarek et al. (2010), Ekren et al. (2010), Wang et al. (2010), Heiz et al. (2011) Ferreira et al.(2013), stated that the aim of the DOE analysis is to perform optimization studies in order to reduce time, effort and cost using minimum resources. Also, to find out which variable has the most significant effect on the performance of system, and which has no impact as well as to identify the interaction among all variables.

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, engine blocks are very complex products and need more than one phase (production line) to be produced. When the engine blocks are moved from phase one to phase two, they are supposed to be within aspects. According to standards, the engine blocks should arrive at phase two with an incoming part temperature between 72-75 ºF. By a cooling process, the temperature of the parts will be reduced to the range between 68-72 ºF. Due to lack of integration between the two phases, sometimes engine blocks arrive with a temperature of 100-108 ºF, so they need more time for cooling. Therefore, significant delays take place in the cooling process due to high incoming temperature. 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 ant entire system by eliminating the bottlenecks in cooling process. Also figure out which is the most significant factor that have potential effect on system and find out the optimal operation conditions that may increase the throughput and improve aver all system efficiency by using experimental design and steepest ascent or descent method.

2. Experimental Procedures

Performing a screening analysis is a very essential approach to screen out all factors that have severe impact on a system. For incoming part temperature and cooling time, Figure 1 shows the mechanism of a part's cooling process. Robots pick up the parts from the part station area and load them up into the cooling tunnel conveyer. An "incoming thermal probe" has been installed at the intake area to measure the incoming part temperature. According to standard, the part is supposed to enter the cooling tunnel with a temperature range from 69 to75 ºF in order to cool it down to 68 ºF. There is an "outcoming thermal probe" to measure the temperature of the exiting part. If the part is within standard (3 Fº), then the program logic controller (PLC) will release the part to the machining processes, otherwise, the part will stay inside the cooling tunnel waiting for releasing.

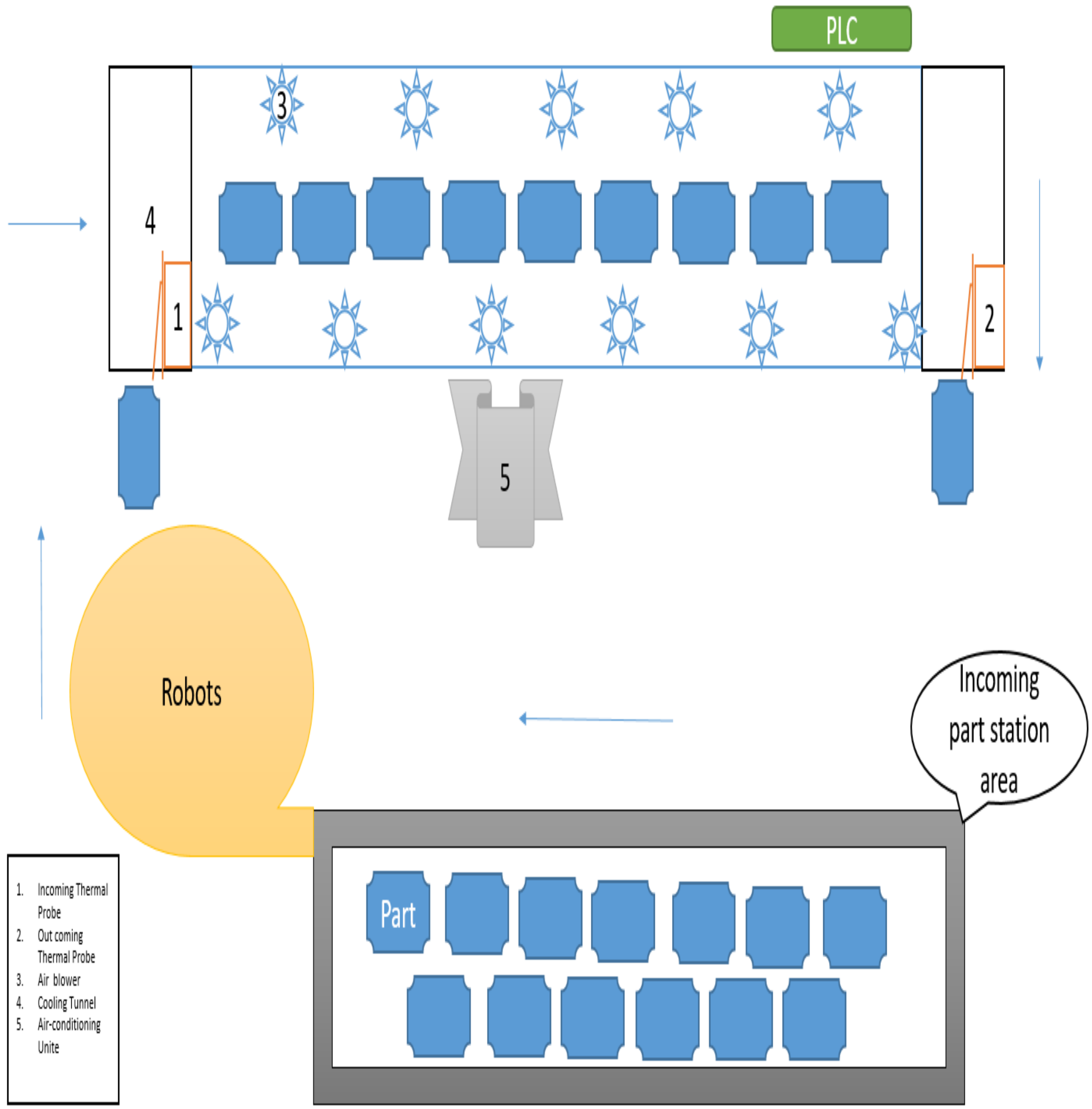

Figure 1. Incoming part temperature measurement

Thermal mapping analysis has been applied on 16 parts to measure the change in length (dimension) of the parts. Coordinate measuring machine (CMM) was used for the measurement. Figures 2a and 2b show how incoming part temperature and cooling time have a drastic effect on the dimensions of the parts.

Figure 2a. Incoming part temperature

2.1 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 (⁰F)**	**B Cooling time (sec)**	**C Soap temperature (⁰F)**	**D Pressure of vacuum chamber (kPa)**	**Treatment Combination**	**Dimension (mm)**
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	

Table 1b. Design levels

Factors	**Unit design** -1	+1
A: Incoming part temperature (⁰F)	72	108
B: Cooling time (sec)	51	59
C: Soap temperature (⁰F)	80	104
D: Pressure of vacuum chamber (kPa)	87	99

2.2 Design Setup

Depending on the above thermal mapping analysis and sediment test, Table 2 shows how the four factors and their interactions within 2 levels affected the coefficient of expansion and the dimension of the part.

Table 2. Design matrix of dimension response

Run Factor	**A Part incoming temperature (ºF)**	**B Cooling time (sec)**	**C Soap temperature (ºF)**	**D Pressure of vacuum chamber (kPa)**	**Dimension (mm)**
1	75	51	80	87	200.045
2	108	51	80	87	200.09
3	75	59	80	87	199.99
4	108	59	80	87	200.025
5	75	51	104	87	200.05
6	108	51	104	87	200.11
7	75	59	104	87	199.98
8	108	59	104	87	200.055
9	75	51	80	99	200.035
10	108	51	80	99	200.1
11	75	59	80	99	199.98
12	108	59	80	99	200.04
13	75	51	104	99	200.05
14	108	51	104	99	200.12
15	75	59	104	99	199.985
16	108	59	104	99	200.045

3.0 DOE Results

The software package Minitab18 has been used to analyze the response of dimension and cleanliness to find out which factor is significant and what kind of relationship was among the factors.

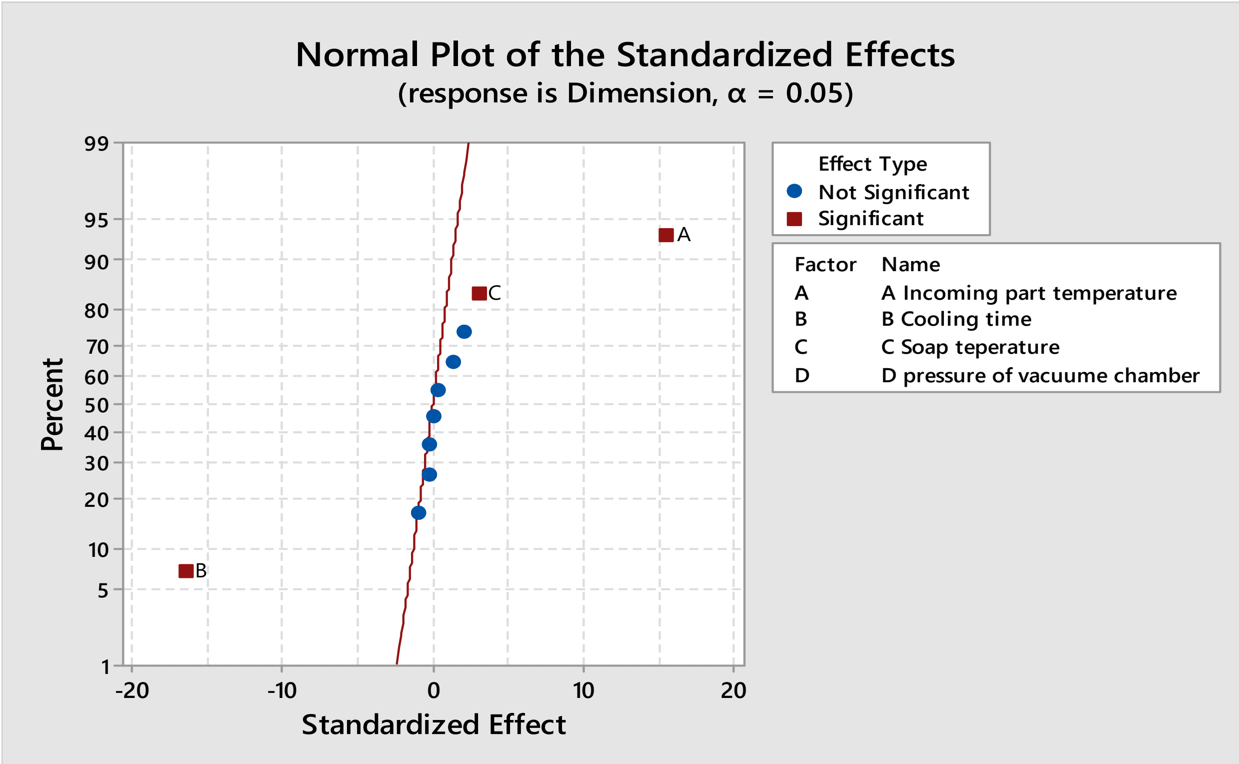

Figure 3. Normal plot of the effect of dimension

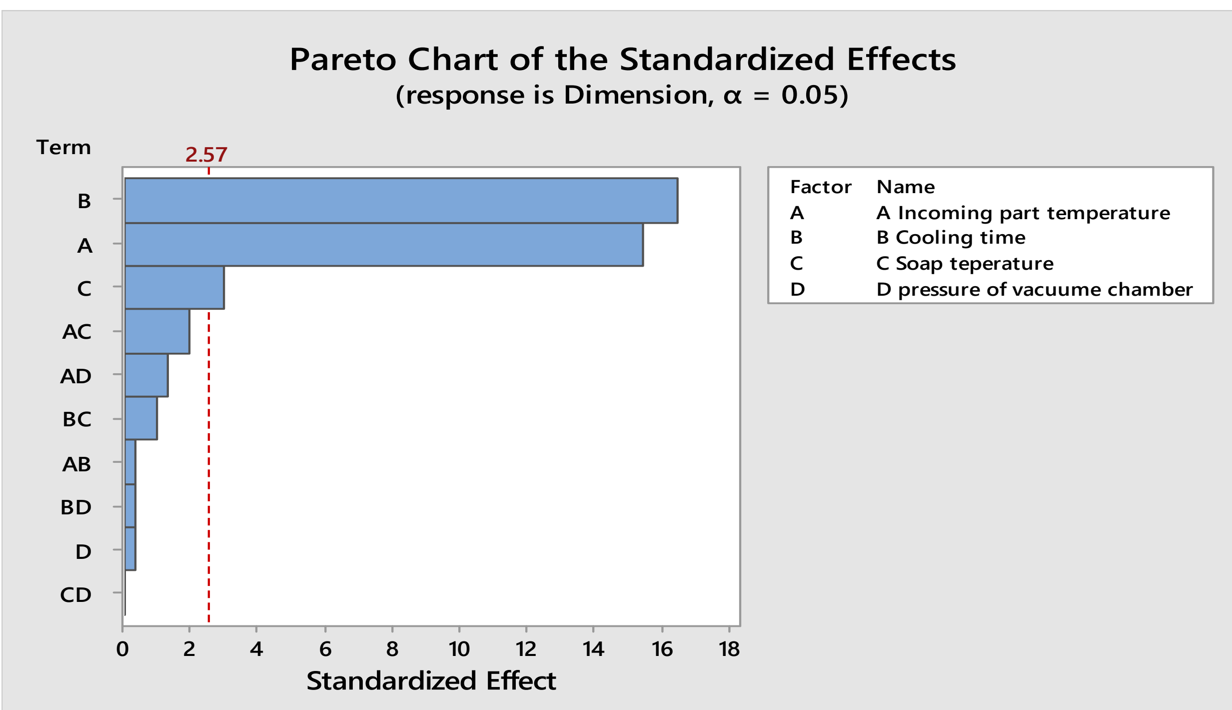

Figure 4. Pareto chart of the effect of dimension

In the middle of Figure 3, the points in blue are in a straight line. They follow a normal distribution. In other words, the distribution is not significant due to their expectation, or the percentile is proportionate to the size of the effect. The ones in red (A, B and C) are outliers and stand away from the ones in the middle. They also indicate that they are not just random noise but there must be a significant affect.

Figure 4 shows a Pareto chart, which quickly shows what is the most important. It also shows the size of the effects and plots the effect size on a horizontal axis ranked from largest to smallest effect. As seen from this analysis, cooling time and incoming temperature have the largest effect on the system.

The check of residuals using Minitab's four-in-one plot is shown in Figure 5. In visually checking the residuals, there are clearly no problems nor any great deviation in the normal probability plot of the residuals. There is nothing very alarming, and it is acceptable.

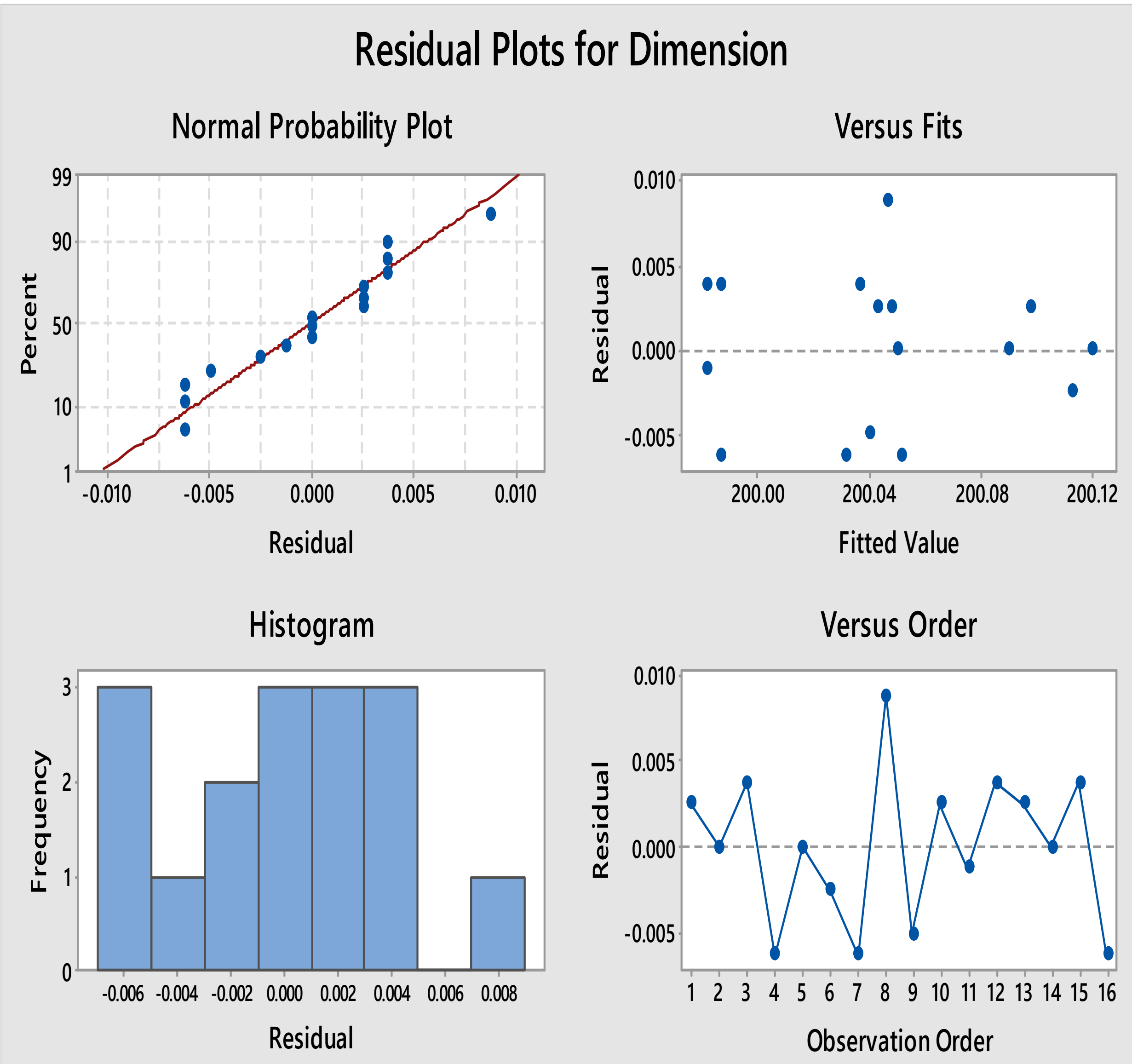

Figure 5. Residual plots for dimension

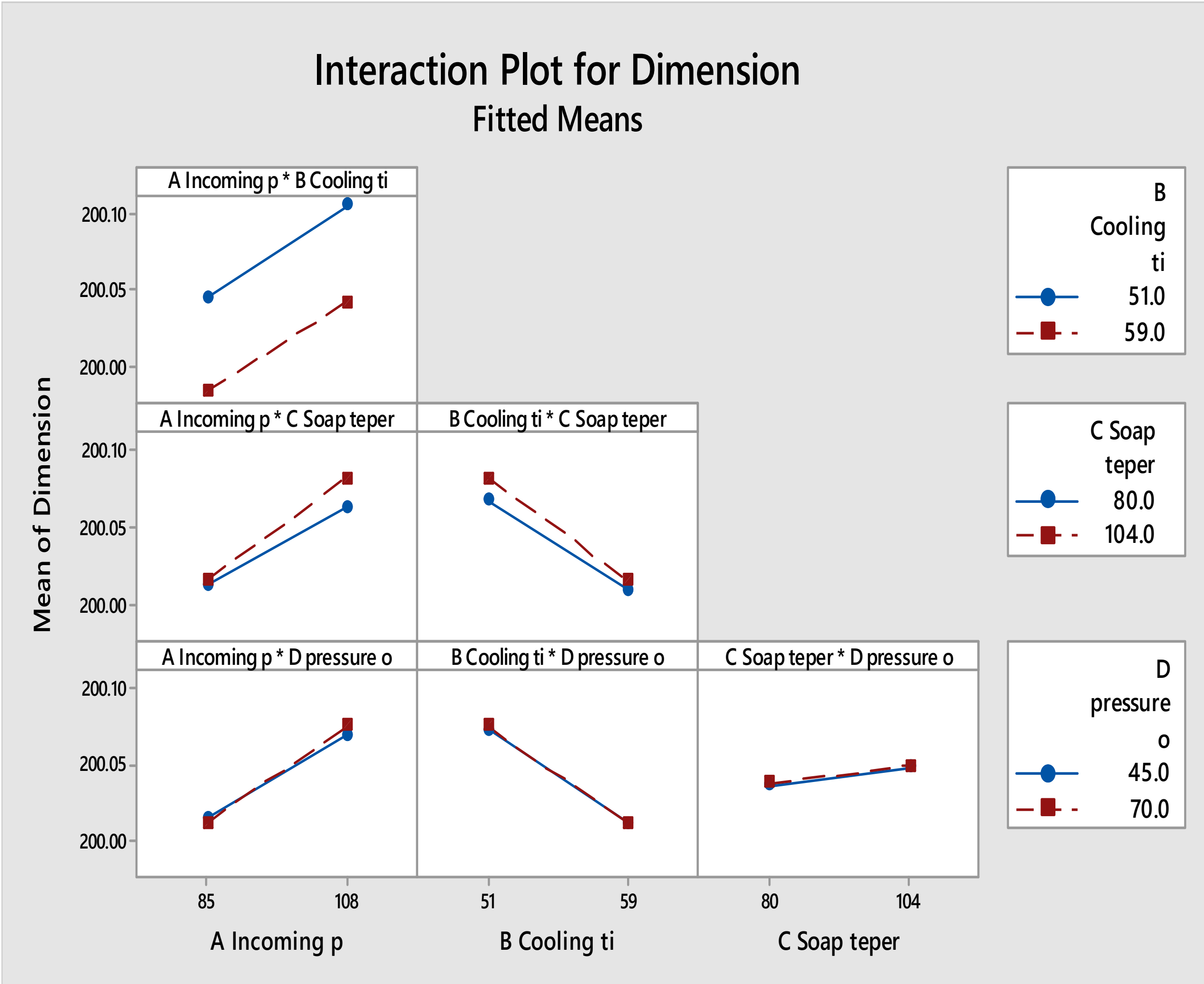

Figure 6. Interaction plot for dimension

Figure 6 shows that the AB, BD, and CD interaction plot lines are almost parallel and, therefore, indicate that interaction effects are not significant. However, the other two combinations, AC and AD, indicate that a medium interaction exists.

3.1 Steepest Descent Method

Steepest descent is a method whereby the experimenter proceeds sequentially along the path of steepest descent, that is, along the path of maximum decrease in the predicted response. The factor levels in natural and design units are as shown in Table 13b.

Dimension = 200.181 + 0.00255 A- 0.007813B + 0.000469C + 0.00005D………………. (1)

Equation 1 represents the linear regression model as it relates to the predicted dimension of the design variables in coded design units. It appears that movement to a region with higher cooling time will lead to a decrease in the predicted response. In addition, a slight decrease in incoming part temperature, soap temperature, and pressure of vacuum chamber may be beneficial. Below calculation shows step-by-step steepest decent method.

From Equation 1, B is selected as the variable to define the step size (note that B is one of the two largest regression coefficients). Let Δ B = b2/ b2 = -0.007813/ - 0.007813 =1

Then from step size equation

Δ A = b1 / b2 = 0.00255/- 0.007813 = - 0.326

Δ C = b3 / b2 = 0.000469/- 0.007813 = - 0.0634

Δ D = b4 / b2 = 0.00005/ - 0.007813 = - 0.0063

The corresponding change in terms of the natural units are:

Δ Incoming part temperature = - (0.326) * ((108 - 75) / 2)) = - 5.38

Δ soap temperature = - (0.0634) * ((104-80) / 2)) = - 0.76

Δ pressure of vacuum chamber = - (0.0063) * ((99- 87)/2)) = - 0.038

Table 3 shows the path of steepest descent in terms of both coded design units and natural units.

Table 3. Path of steepest descent

	Coded Variables				**Natural Variables**			
Factor	A	B	C	D	°F	Sec	°F	kPa
Base	0	0	0	0	91.5	55	92	93
Δ	-0.326	1	-0.0634	-0.0063	- 5.38	1	-0.76	-0.038
Base+ Δ	-0.326	1	-0.0634	-0.0063	86.12	56	91.24	92.962
Base+2Δ	-0.652	2	- 0.128	-0.0126	80.74	57	90.48	92.924
Base+3Δ	-0.978	3	-0.19	-0.189	75.36	58	89.72	92.886

4. Conclusion

Significant improvement on overall system efficiency has been achieved after applying design of experiment, steepest descent. These methodologies provide an excellent perspective to find another region for improvement and, then, the optimal setup. The strategy involves making experimental runs along this path until no improvement in response of dimension is observed. Also, the table shows the improvement and optimum data of all natural variables, especially cooling time, which is 57 sec instead of 55 sec. That leads to: reduction in the delay time, elimination of bottlenecks in cooling process and reduction in downtime and increase in uptime of the system. Also decrease in scrap and bad parts as well as 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 1564 part per day.

References

Nadia Bhuiyan, Gerard Gouw, and Dayoosh Yazdi, "*Scheduling of a computer integrated manufacturing system,"* A simulation study JIEM, 2011 – 4(4):577-609, 2013, Online ISSN: 2013-0953 – Print ISSN: 2013-8423 http://dx.doi.org/10.3926/jiem.331.

Ahad Ali, Annamalai Pandian, *"The Effects of System Failures in a Robotic Assembly Line-Simulation Modeling and DOE Analysis*," Proceedings of the 2014 International Conference on Industrial Engineering and Operations Management, Bali, Indonesia, January 7 – 9, 2014.

AlGeddawy Tarek and ElMaraghy Hoda, *"Design of single assembly line for the delayed differentiation of product variants,"* Flexible Services & Manufacturing Journal, Dec 2010, Vol. 22 Issue 3/4, pp. 163-182.

B.Y. Ekren, S.S. Heragu, A. Krishnamurthy, and C.J. Malmborg, *"Simulation based experimental design to identify factors affecting performance of AVS/RS, Computer,"* Ind. Eng., 58 (1), 2010, pp. 175–185.

B. Wang, Y. Jin, and Y. Luo, *"Parametric optimization of EQ6110HEV hybrid electric bus based on orthogonal experiment design*," Int. J. Automot. Technol., 11 (1), 2010, pp. 119–125.

J. Heiz and B. Render, *"Operations Management*," 10th Edition, Pearson, ISBN: 9780136119418, 2011.

J.C.E. Ferreira and P.A. Reaes, "*Performance Comparison of the Virtual Cell Layout with Cellular and Job Shop Configurations Using Simulation and Design of Experiments*," IEEE International Conference on Automation Science and Engineering (CASE), 2013, pp. 795-800.

Johnson, R.T., Hutto, G.T., Simpson, J.R. & Montgomery, D.C., 2012, *'Designed experiments for the defense community',* Quality Engineering 24(1), 60–79.

Nikhil Shintre, "Application of Lean in Product and Manufacturing Engineering," *Geometric Limited*, January 2010.

M .Ishtiaq Hussain, "Oil gallery hole drilling in aluminum alloy engine blocks using minimum quantity lubricant (MQL) method," Lawrence Technological University, 2008, 3339271.

Raymond H. Myers, D. Montgomery and Christine M. Anderson, "Response Surface Methodology," third edition, *Wiley Series Probability and Statistics*, 2009.

Waseem Jaradat, "Impact of operation testing and interior trim manufacturing on head injury criterion," Lawrence Technological University, 2006.

Cheles Ebeling, "An Introduction to Reliability and Maintainability Engineering," second edition.

Box and Behnken, "Some new three level designs for the study of quantitative variables," *Technimetrics*, vol.2, no.2, November 1960, pp. 445-475.

K. Taraman, J. Hazra, and E. Kennedy, "Computerized machinability system," *4th International Conference on Production Research*, Tokyo, Japan, August 1977, pp. 1-9.

R. Myers and D. Montgomery, *Response Surface Methodology - Process and Product Optimization Using Designed Experiments, Second Edition,* John Wiley & Sons, Inc.,

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.

EDUCATION
Doctor of Engineering in Manufacturing Systems, Lawrence Technological University Southfield, MI USA, 2008
MS (Honors) in Manufacturing Systems, Lawrence Technological University Southfield, MI USA, 2006
MS (Honors) in Quality Control, Eastern Michigan University, Ypsilanti MI USA, 2003
BSc in Mechanical Engineering, University of Engineering and Technology Lahore, Pakistan, 1988
Eight weeks of intensive management training at University of Guam, USA

PROFESSIONAL CERTIFICATIONS
Certified Mechanical Inspector (CMI) American Society for Quality (ASQ)
Certified Six Sigma Black Belt from General Motors University
Certified Six Sigma Coach from General Motors University