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IMPROVING THERMOFORM PRODUCTIVITY: CASE OF DESIGN-OF-EXPERIMENT

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ABSTRACT

This work is aimed to improve productivity of single-stage thermoforming process by implementing Six Sigma methodology. The process is performed at a refrigerator manufacturing company in a developing country. Six Sigma methodology – Define, Measure, Analyze, Improve, and Control (DMAIC) and Design of Experiment (DOE) is used to identify the critical factors that affect a thermoforming process's productivity and to determine their optimal configuration using Response Optimization. The critical factors identified are: sheet temperature; sheet thickness, and; vacuum time. Optimization of these factors resulted in increased productivity of 13%, while maintaining quality. Increased productivity helped the company in minimizing the buffer stocks and the associated costs. This work revealed that single-stage thermoforming process can be made more productive by installing a pre-heating stage before inserting sheet in the machine, as it will save the critical time. For further study, more thermoforming material can be included in DOE as compared to ABS plastic which is in scope of this study.

Keywords: *Design of experiment, DOE, response optimization, six sigma, thermoforming.*

1) INTRODUCTION

In this modern era of manufacturing, industries are heavily investing for reduced manufacturing lead times of the products. In developed countries, most of the manufacturing is related to assembly whereas core manufacturing processes are out-sourced. In developing countries, like Pakistan, out-sourcing is less preferred as compared to 'vertical integration' where industries work as complete manufacturers of products, i.e. from raw material to sub-assembly and then final product assembly. Also, main focus of improvement is usually the assembling processes' cycle time, while manufacturing processes are often overlooked. This work is performed in a Refrigerator Manufacturing Company in Pakistan which is producing most of its sub-assembly parts in-house. Thermoforming is one of the processes performed in-house for manufacturing different liners of Acrylonitrile Butadiene Styrene (ABS) material. Hot sheets are pressed against the mold, taking its shape and design, thus desirable parts are made. It is a critical process because achievement of uniform material distribution and desired quality of parts is pivotal.

Thermoforming process involves: sheet clamping (throughout the cycle); heating up to thermoforming temperature (so that parts have desired mechanical properties); forming by molds (vacuum forces give the sheet the shape of mold); cooling in ambient air (and by blowers to solidify the part and easily detach it from the mold), and; finally, trimming is done to remove the unwanted material from the finished part, Moore (2002). Thermoforming process has several limitations, such as: part designs that can be made; material selection, and; temperature constraints (Moore, 2002).

The company, in focus, is facing low productivity issues in thermoforming process due to which the company has to carry large buffer stocks for smooth production at assembly line. The largest cycle time at thermoforming station therefore, makes it the bottleneck station in the whole system. Therefore, refrigerator in-liners' production (i.e. the thermoforming process) is taken as a Six Sigma project for productivity improvement. This approach of selecting the bottleneck is also referred to as the Theory of Constraints, Goldratt, Cox, and Whitford (2004); Rand (2000) . The cycle time of a liner produced by single-stage thermoforming was 140 seconds before improvement. Generally, the aim is to improve productivity by inexpensive methods, and specifically, to identify the factors having major impact on the process's cycle time along with their optimal setting or configuration.

2) LITERATURE REVIEW

Six Sigma is an improvement methodology used in both manufacturing and service industries throughout the world, Qureshi, Bashir, Zaman, Sajjad and Fakhr (2012); Waseem, Zulqarnain, Khalid, and Saleem (2015); Zulqarnain, Iqbal, and Khalid (2013). It evaluates the capability of a process to produce defect-free products, where a defect is defined as anything that results in customer dissatisfaction Hung & Sung (2011). The immediate goal of Six Sigma methodology is defect reduction. As a chain reaction, reduced defects lead to yield improvement, and higher yields improve customer satisfaction. Six Sigma can also be defined as a toolset, and not a management system, which is best used in conjunction with other more comprehensive quality standards, such as the Baldrige Criteria for Performance Excellence or the European Quality Award (Raisinghani, Ette, Pierce, Cannon, & Daripaly, 2005).

Six Sigma, similar to other quality management initiatives, requires transformation in organization's culture to achieve the desired results. Six Sigma projects can be classified as (Koning, 2007):

- Decreasing operational cost by improving processing efficiency;
- Decreasing operational cost by using cheaper channels;
- Increasing revenue by increasing customer satisfaction;
- Increasing revenue by servicing more customers;
- Decreasing operational losses, and;
- Improving business decision making.

There are several approaches under Six Sigma methodology; DMAIC (Define, Measure, Analyze, Improve and Control) is one of them. Pyzdek (2003); Pyzdek and Keller (2014); DeHart (2015); Andersson, Eriksson, and Torstensson (2006) can be referred for a detailed discussion on other approaches. DMAIC is a systematic approach to process optimization where a goal is set by the team with clear timelines. It provides a guideline for each phase and has phase-wise specified tools and techniques, Deshpande, Makker, & Goldstein (1999). It directs the process in a direction where customer requirements are met. In this study, our especial focus is on the improve phase, where Design of Experiment (DOE) is carried out.

Statistical DOE refers to the process of experimental planning so that appropriate data, analyzable by statistical methods, can be collected, Sematech (2003). This results in objective and valid conclusions. Well-chosen experimental design maximizes the amount of information that can be obtained from a given amount of experimental effort, and some guidelines for this are (Montgomery, 2007):

1) Recognition of and statement of the problem;
2) Choice of factors, levels and ranges;
3) Selection of the response variable;

4) Choice of experimental design;
5) Perform the experiment;
6) Statistical analysis of the data, and;
7) Conclusions and recommendations.

DOE has many uses for the practitioners, as it helps in: choosing between alternatives; selecting the key factors affecting the response, and; regression modeling etc.

2.1) Thermoforming process

This work focused on improving thermoforming process which involves five main steps: (a) sheet clamping; (b) heating; (c) forming; (d) cooling, and; (e) trimming. It also requires trained personnel to smoothly produce products with uniform quality. Each step involved in thermoforming process can be defined as (Adler, 2007):

2.1.1) Sheet clamping

Clamping functions include transporting and securely holding the sheet during heating, forming and cooling phases of the process so that, no wear and tear occurs due to sheet slippage, and corner tearing etc.

2.1.2) Sheet Heating

It involves selection of heaters, and; machine and parameter settings considering the material being heated. Heating is normally performed by two heater banks that heat the sheet from both sides so that temperature gradient across the sheet thickness should be minimized (Boser, 2006).

2.1.3) Forming

As the sheet reaches thermoforming temperature, the mold comes into contact with the sheet and sheet takes the shape of the mold. Before the mold contacts the sheet, a balloon of sheet is made by air which is called pre-blow (Braker, 2010).

2.1.4) Cooling

After molding, cooling mechanism of the machine is used to cool the molded part, so that material solidifies and takes the final shape and can easily be taken out. Cooling mechanisms involve the blowing fans on the top of the machine, and water spray / chilled-air accelerate the cooling.

2.1.5) Trimming

Removing the unwanted material from the final product is called trimming. It can be achieved by hand sawing, dies with ruled blades and hydraulic/pneumatic blades with the part guided manually by the worker.

Besides these steps, material specification plays a vital role in parts' quality and characteristics. Thermoforming materials can be divided into two categories namely: Amorphous Thermoplastics and Semi-crystalline Thermoplastics. Amorphous Thermoplastics are characterized by a high level of optical transparency, provided they are produced without additives DOW Plastics (1992). Applications of amorphous thermoplastics are usually below glass transition temperature (TG) as this range gives a high level of strength. Semi-crystalline materials are generally opaque to translucent. Below TG, they are extremely brittle and are then only used in special conditions. These materials are normally deployed when the temperature ranges between TG and crystalline melting temperature, as then the mechanical properties are better (SIMONA, 2005).

3) RESEARCH METHODOLOGY

This research has used case study methodology to explore and comprehend complex issues, as discussed by Zainal (2007), related to diminishing productivity of thermoforming, and consequently huge quantity of buffer stocks has to be maintained by the company for stable functionality of the assembly line. For this study, fieldwork was conducted on the assembly line of thermoforming station and, unstructured and qualitative interviews, as suggested by Noor (2008), were collected from Marketing, Engineering and the very next station (i.e. forming) to gain understanding about the critical aspects of thermoforming. Moreover, Zainal (2007) prescribed that a combination of qualitative and quantitative data should be incorporated into the case studies to gauge deeper aspects of the concerning issue. Hence, the study has used experimental research design through Design-of-Experiment (DOE) for six sigma implementation after collecting quantitative data, whereas, unstructured interviews were used for gathering qualitative data. Stop watch studies were further conducted where data on process times were not present. Collected data from the experiment then were analyzed statistically to understand the phenomenon, Pyzdek (2003) and Pyzdek and Keller (2014). Additionally, Minitab software was used to analyze statistical data as collected from the designed experiment.

4) IMPLEMENTING SIX SIGMA ON THERMOFORMING

This study aims to improve the productivity of a Single-Stage Thermoforming machine, which produces internal lining (called as 'part' interchangeably) of refrigerator body. This machine consisted of: framework unit; heating station; mold table; hydraulic system; pneumatic system; cooling system, and; PLC (programmable logic controller) enabled electric system. The current production rate is 27 liners per hour, making the cycle time as 140 seconds per liner. The target is to increase the production rate and decrease the cycle time by 10% at improved or same quality. Moreover, it is desired to identify the significant factors which control the cycle time of the process. DMAIC approach was implemented for this purpose, with especial focus on DOE in the improve phase. Phases of DMAIC along with their findings are now presented.

4.1) Define phase

In this phase, the project charter was created to present the project to senior management. It included current data regarding production rates and targeted cycle time at project completion. In the absence of any local benchmark, after discussions the team decided an increase of 10% in productivity as the target, as it seemed realistic but challenging. Supplier-Input-Process-Output-Customer (SIPOC) chart of thermoforming process was then developed and Figure 1 shows a brief SIPOC.

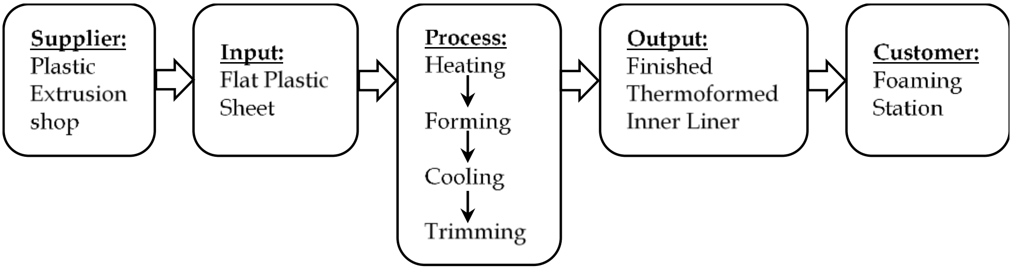

Figure 1: Higher-level SIPOC of Thermoforming Process

Voice of Customer (VOC) analysis was done by interviewing the marketing and the engineering departments along with the next station's supervisor. Marketing and engineering provided the information about the thermoformed part's quality, while next station's requirement was part's availability. Characteristics that are Critical to Quality (CTQs) and Critical to Delivery (CTDs) were defined from VOC at this stage (see DeHart (2015); Pyzdek (2003); Pyzdek and Keller (2014) for further description about CTx). CTQ for thermoformed part is the uniform wall thickness of plastic across the final part or within defined engineering limits. The cycle time of thermoforming station was defined as the CTD for the project. CTD is in the scope of this six sigma project, as mentioned under the discussion of project charter.

4.2) Measure phase

In this phase, data were collected for the cycle time of different stages of thermoforming and found to be 139.77 sec. The time of different tasks involved are given in Table 1.

Table 1: Distribution of Cycle Time in Thermoforming Operations

Sr. No.	Process Description	Time observed (seconds)	% Contribution (rounded)
1)	Sheet loading Time in clamping frame	13.13	9%
2)	Heater banks positioning Time on sheet	10.49	8%
3)	Heating Time	61.30	44%
4)	Heater banks going back time to their position	6.21	4%
5)	Pre Blowing Time	1.55	1%
6)	Forming Time	10.29	7%
7)	Vacuuming Time	15.00	11%
8)	Cooling Time	14.00	10%
9)	Shake out Time	3.00	2%
10)	Part Unloading Time	4.80	3%
	Total	**139.77**	**100%**

Table 1 shows that heating time makes the maximum portion of the cycle time and thus, improving heating time will substantially impact productivity. Therefore, a study was conducted to investigate the factors related to heating of the thermoforming plastic sheet. Research articles and thermoforming manuals were consulted to find the factors that affect the heating time of the plastic sheet, ChemCast (2002); Gruenwald (1998); Throne (1987). Table 2 shows the factors that have an influence on thermoforming process.

Table 2: Factors affecting Thermoforming Process

Sr. No.	Category	Variables
1)	Material	▪ Sheet thickness
2)		▪ Sheet pigmentation
3)		▪ Sheet size
4)		▪ Temperature uniformity
5)	Mold	▪ Vacuum bores or orifices
6)		▪ Mold surface
7)		▪ Mold temperature
8)		▪ Mechanical support temperature
9)	Pre-Stretching	▪ Vacuum box
10)		▪ Air temperature
11)	Mechanical Support	▪ Mechanical support form
12)		▪ Support materials
13)		▪ Support temperature
14)		▪ Support surface
15)		▪ Support height
16)		▪ Support vacuum speed
17)		▪ Support depth of action
18)		▪ Material variables when forming with support

4.3) Analyze phase

All factors listed in Table 2 have influence on thermoforming process. Some have more influence than others. A discussion on these factors follows.

4.3.1) Sheet thickness

Thickness plays an important role when sheet size is constant. Proper thermoforming requires the sheet's core layer to be at thermoforming temperature. Thick sheets require more heat energy to soften as well as more time to take the core layer temperature to forming temperature Li, Ma, Xuan, Seol, & Shen (2010). Sheet thickness is selected for further analysis because of its criticality.

4.3.2) Sheet pigmentation

Sheet pigmentation can change heating requirements, however due to our inability of changing any material composition this factor was taken as constant.

4.3.3) Sheet size

Sheet size has direct effect on the material distribution and heating controls. According to company guidelines, the size of sheet is fixed and hence this factor was taken as constant.

4.3.4) Temperature uniformity

This factor is uncontrollable during the heating phase of thermoforming but sheet's initial temperature can definitely be taken into account as it defines the delta between initial and required (for thermoforming) temperatures. If the sheet's initial temperature is high, then amount of heat and time required to reach forming temperature will be less.

4.3.5) Vacuum bores or orifices

This factor is important in mold design which is out of scope of this study and hence was not considered for further study.

4.3.6) Mold surface

It is a critical factor for part's surface, as the sheet completely takes the shape of the mold. This factor does not affect the cycle time of thermoforming process and was not selected.

4.3.7) Mold temperature

Mold temperature is controlled so that the sheet is provided with an appreciable temperature creating the pattern without developing thermal stresses in the thermoformed part. When mold comes into contacts with the sheet, it takes away the heat from the sheet as it is at a lower temperature than the sheet. Improper mold temperature will cause sheet damage when stretching takes place. This factor may have substantial influence on the cycle time, and therefore was selected for further analysis.

4.3.8) Mechanical support temperature

This factor is related to stretching marks at the corners of the part. The machine has no option for temperature control of the mechanical support; hence this factor was not considered.

4.3.9) Vacuum box

This feature is not available in the machine, but vacuum time was selected instead, as it has the second largest contribution in cycle time (see Table 1). It is the time required to remove the air present between sheet and mold, ensuring the sheets exactly come into contact with mold and final shape is formed.

4.3.10) Air temperature

Air temperature is controlled for different operations such as pre-blowing and shake-out etc. It should be 10% below sheet's temperature; however this has no significant effect on the cycle time (ChemCast, 2002).

4.3.11) Other factors

All remaining factors related to mechanical support does not have any significant impact on cycle time. This was discussed in one of the team's brainstorming sessions. Finally, four factors were selected from the initial 18 factors. In light of Table 1, the team found these four factors to be the most critical:

1) Sheet Thickness (t);
2) Sheet's Initial Temperature (T_s);

3) Mold Temperature (T_m), and;
4) Vacuum Time (V_t).

It was decided to perform DOE on these selected four factors.

4.4) Improve phase

Design of experiment is used in improve phase of DMAIC. In terms of DOE requirements, the guidelines followed here is similar to Zulqarnain et al. (2013), the CTD or cycle time (C_t) required to produce a single refrigerator liner is the Key Process Output Variable (KPOV) or the response variable. The four variables, selected in measure phase, are the Key Process Input Variables (KPIVs).

Since complete DOE has been performed using statistical software package "Minitab", the sequence of steps in the development are identical as per software structure. In order to achieve statistical confidence and keep the experimental cost controllable, two levels are selected for each factor, as shown in Table 3.

Table 3: Levels of Input Variables for conducting DOE

Sr. No.	Input Variable	Level (Low)	Level (High)
1)	Sheet Thickness	2.40 mm	2.45 mm
2)	Sheet Temperature at start of Heating	30^o C	55^o C
3)	Vacuum Time	9 sec	15 sec
4)	Mold Temperature	80^o C	90^o C

Table 4: Standard Values used in Minitab Calculations

Alpha	Std. Dev.	Factors	Base Design	Center Points	Effect	Reps	Total Runs	Target Power	Actual Power
0.05	1	4	$2^4 = 16$	0	2	2	32	0.9	0.999

Number of replicates of the experiments is determined using standard feature of Minitab known as "Power and Sample Size tool". Table 4 shows the input and output parameters for power and sample size. It indicates that two replicates are necessary to achieve 90% power for the experimental model. Since Full Factorial DOE is used, therefore, all terms are free from aliasing (which occurs in fractional factorial designs). Then, experiments run order was produced by Minitab in randomized manner.

In order to check consistency and adequacy of the data, residual plots (see Figure 2) are developed that determine the state of data and any abnormality in the data collection. Histogram shows that data are distributed about mean and there is no existence of outliers. In the same way, it is evident from Normality probability plot that data are normally distributed. Residuals versus Fitted values graph indicates that variance is constant and outliers do not exist. Residuals versus order of the data show that data have no systematic effects due to time or data collection order. In conclusion, the data collected are free from systematic effect, non-linearity, non-normality, outliers, variance inconsistency and skewness.

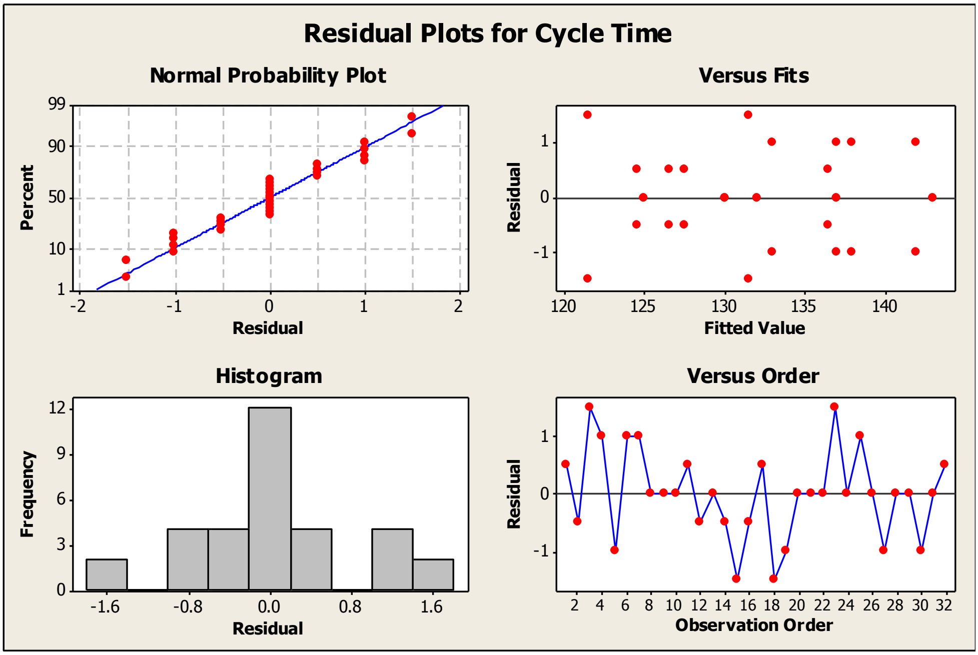

Figure 2: Residual Plots for Cycle Time from Minitab

Table 5: Significant Factors and Interactions

Sr. #	Factor/Interaction	Effect	Inference
1	Sheet Temperature	-10.250	It has highest effect on the response variable. Negative sign indicates that high initial sheet temperature will decrease the cycle time significantly.
2	Vacuum Time	+5.375	It shows that vacuum time can reduce the cycle time significantly.
3	Sheet Thickness	+3.375	It is evident that lower thickness (up to acceptable lower limit) is recommended to reduce cycle time.
4	Sheet Thickness × Sheet Temperature	-1.250	It has the smallest effect on the response variable. Negative sign indicates that both will decrease response on increase in their levels.
5	Sheet Temperature × Mold Temperature	-1.250	It has the smallest effect on the response variable. Negative sign indicates that both will decrease response on increase in their levels.

Interactions of factors and main effect of response variance are determined using Factorial fit analysis, performed in Minitab. The interactions and factors having p-value ≤ 0.05 are considered as significant. Table 5 shows the significant factors and interactions. Same results are evident from interaction plots shown in Figures 3 and 4.

The effects of all significant factors and interactions are of interest in further analysis. The regression equation from the factorial fit analysis for cycle time (C_t) is shown below:

$$\begin{aligned}\mathbf{C_t} = {} & 132.187 + 1.687\,(\text{Sheet Thickness}) - 5.125\,(\text{Sheet Temperature}) - 0.188\,(\text{Mold Temperature}) \\ & + 2.688\,(\text{Vacuum Time}) - 0.625\,(\text{Sheet Thickness*Sheet Temperature}) \\ & + 0.312\,(\text{Sheet Thickness*Mold Temperature}) + 0.063\,(\text{Sheet Thickness*Vacuum Time}) \\ & - 0.625\,(\text{Sheet Temperature*Mold Temperature}) + 0.000\,(\text{Sheet Temperature*Vacuum Time}) \\ & + 0.312\,(\text{Mold Temperature*Vacuum Time}) \\ & + 0.375\,(\text{Sheet Thickness*Sheet Temperature*Mold Temperature}) \\ & - 0.125\,(\text{Sheet Thickness*Sheet Temperature*Vacuum Time}) \\ & + 0.187\,(\text{Sheet Thickness*Mold Temperature*Vacuum Time})\end{aligned}$$

+ 0.250 (Sheet Temperature*Mold Temperature*Vacuum Time)
+0.125 (Sheet Thickness*Sheet Temperature*Mold Temperature*Vacuum Time)

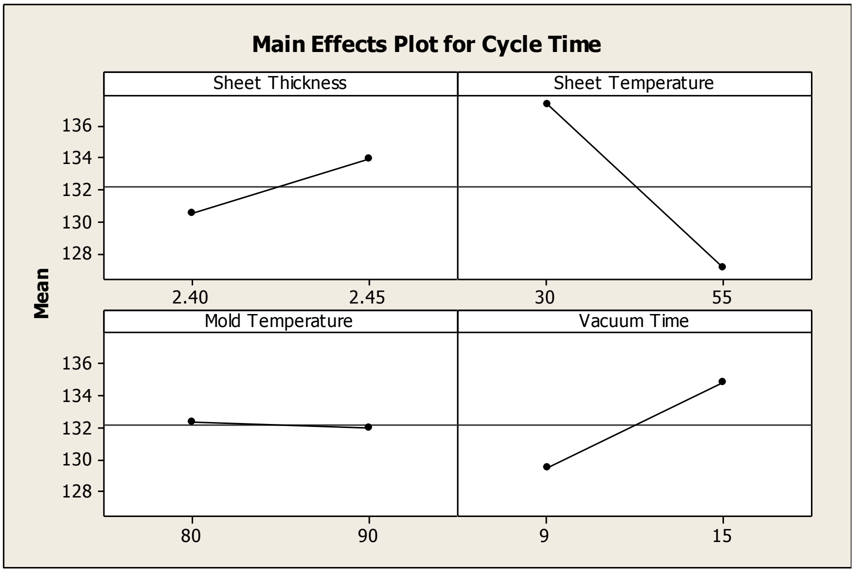

Figure 3: Main Effects Plot of Cycle Time

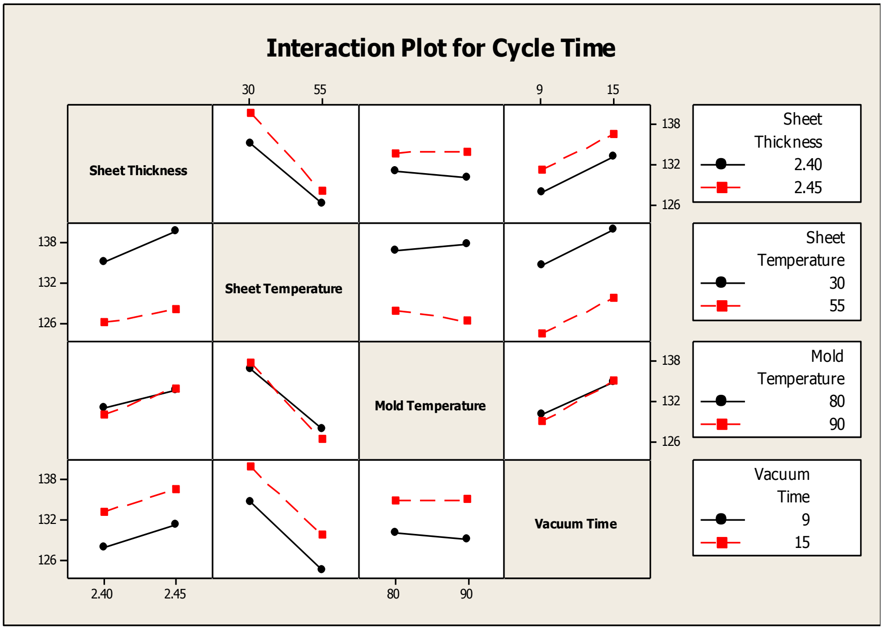

Figure 4: Interaction Plot for Cycle Time

R-square value is 98.45%, therefore, the model almost completely explains the proportion of variability present. The predicted R-square is 93.79% which means that the future values given by the model will be more than 90% reliable.

The analysis from the factorial fit can be proved further with the help of Main Effect graph, Interaction graph, Normal Plot of standardized effects, Half Normal plot of standardized effects and Pareto chart of standardized effects.

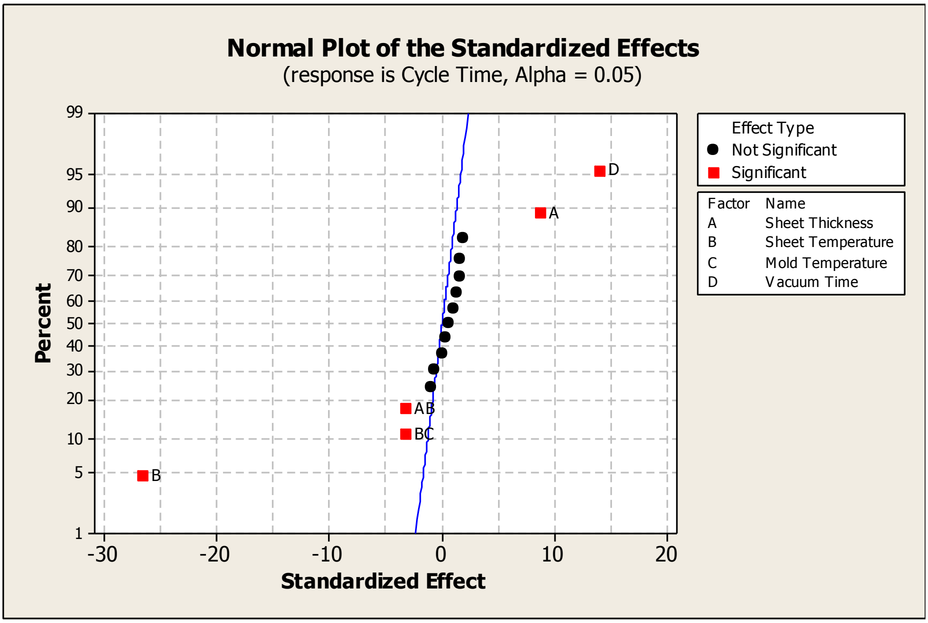

Figure 5: Normal Plot of the Standardized Effects

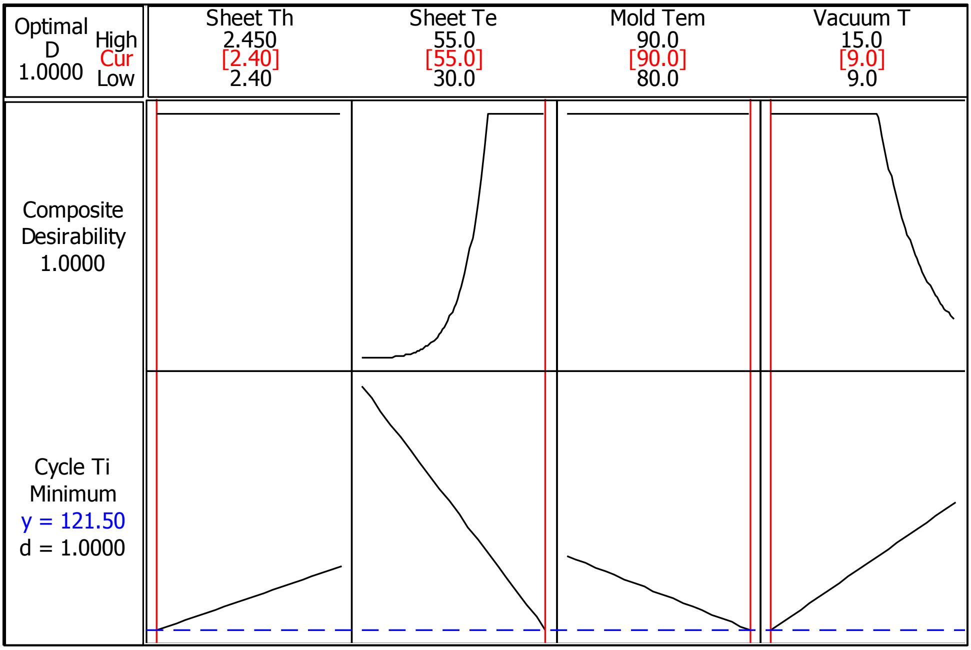

Figure 6: Optimal Response using Response Optimizer Technique

Normal plot of Standardized Effects compare the relative magnitude and significance of both main and interaction effects, as shown in Figure 5. In this chart, squares are defined as significant because they lie farthest from the fitted line, while other lying near the line have negligible effect on the response variable, thus, substantiating the earlier findings.

4.4.1) Determining optimal solution

DOE concludes that the sheet thickness (t), sheet temperature (T_s) and vacuum time (V_t) have the major impact on cycle time. In order to find their optimal values, Minitab's tool Response Optimizer is used, where the objective function is minimization of cycle time (C_t).

4.4.2) Outcome of the response optimizer

The outcome of the response optimizer is shown in Figure 6. The optimized values determined by Response Optimizer are given in Table 6. The cycle time found at optimized values from response optimizer is 121.50 sec, as compound to 139.77 sec. This means that the DOE has improved the cycle time by 13.1%.

Table 6: Output Values of Factors from Response Optimizer

Sr. No.	Factor Description	Optimized Values
1)	Sheet Thickness	2.40 mm
2)	Sheet Temperature	55°C
3)	Mold Temperature	90 °C
4)	Vacuum Time	9 sec

4.5) Control phase

Results, derived from the improve phase, are implemented on the thermoforming process. Monitoring of the next 1000 refrigerator liners produced, show improvement in productivity by almost 13%. The quality of the liner in this trial lot is checked and has been found same as before. The optimized parameters are in the documentation process i.e. these are explicitly mentioned in the Standard Operating Procedure (SOP) and Work Instructions (WI) of the thermoforming process in the company. This will serve as the control plan, i.e. where the critical process parameters are frozen.

5) CONCLUSION

This work presents a case of six sigma implementation using Define, Measure, Analyze, Improve, and Control (DMAIC) approach for improving the productivity of thermoforming process in a manufacturing company of a developing country. It revealed that elevated sheet temperature can increase the productivity of thermoforming, as well as vacuum time. Sheet thickness is another critical factor impacting productivity, i.e. higher the thickness, higher the heating energy and time required to heat the sheet. Mold temperature was found to have the least impact on productivity; however, it remains a critical parameter for part's quality. This successful implementation will help in increasing the use of six sigma methodology in addressing other problems of the company.

This project has identified several other potential opportunities for future work which are as follows. (a) This project was limited to single material, i.e. Acrylonitrile Butadiene Styrene (ABS) plastic, and the scope can be expanded to other thermoforming materials. (b) The company has three suppliers for ABS material which have different properties like Mass Flow

Index (MFI), Glass Transition Temperature and Flexural Modulus etc. These properties can be studied for determining the best ABS material to achieve the optimum results. (c) Moreover, there are 320 heaters for heating the sheet which are set using the PLC screen. These settings are considered as constant in the scope of current project but these settings can also be altered for further process improvement.

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