A Taguchi-Continuous Simulation Approach to the Injection Molding Blowing Process Quality Improvement

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***Abstract*— Numerous operational parameters affect the performance of the injection blow molding process, hence, complicating its' controlling and improving functions. The current research presents a combined Taguchi-continuous simulation approach for improving the quality of this process. Continuous simulation modeling was built based on actual experiments, then, was used to provide data for Taguchi analysis as well as for conducting confirmation experiments. Taguchi method was employed to identify significant parameters' associated with their levels for achieving optimum process quality indicators. The implementation of the proposed approach in the production of Polyethylene bottles revealed that the most significant parameters for the injection blow molding of bottles are center mold temperature, the first blow air, the melting temperature, and the blow air delay. By adopting the optimum levels of these parameters the process waste percentage was reduced from 4.54% to 0.32%; which validates the aptness of the approach.**

Keywords*— *injection blow molding; Taguchi method; continuous process simulation; Polyethylene bottles

I. INTRODUCTION

As other manufacturing processes, injection blow molding process continuously strive to improve quality. Generally, main causes of quality problems in injection molding are material related defects such as black spots, operational related defects such as flash, and post-molding based defects such as inhomogeneous product thickness [1]. Numerous operational parameters affect the quality of the injection blow molding process in mutual interactions with each other and with other factors such as mold design components. Inappropriate settings of such parameters would dramatically increase defective products percentage. Therefore, in order to optimize the quality of the process, the parameters settings must be simultaneously determined.

Design of experiment (DoE) is a very useful statistical tool to design and analyze complicated problems with multi inputs affect single or multi responses, which are usually critical to quality characteristics, in a coinciding manner. It helps to investigate how inputs affect responses and to determine optimal inputs parameters [2]. Taguchi method is a DoE approach that has been used by several researchers to optimize such complicated problems including the injection molding process; mainly considering the process parameters, and in some studies, also including molding design elements. Kamaruddin et al [3] applied Taguchi method to improve the shrinkage of a plastic blend considering the parameters of injection speed, melting temperature, injection pressure, holding pressure, holding time, and cooling time. Hussein et al [4] selected similar parameters but also included the runner size as an input parameter while trying to minimize warpage defects. Also aiming to minimize warpage, Jain et al [5] mentioned other parameters such as gate position and granules moisture. All the above three research [3-5] used the signal-to-noise (S/N) ratio and orthogonal array tools of Taguchi's parameter design and concluded that Taguchi method is appropriate to solve the injection molding quality problems. Lo et al [6] employed Taguchi method for: 1) screening pertinent process parameters in the lenses injection molding process, and 2) in confirmation experiments for optimal process's factors settings that resulted from the analysis. The results provided substantial improvement for the profile accuracy of lenses and defectives were reduced from 43,331 to 0.07 part per million.

Computer simulation has been used since the early 1970s to study the injection molding process and its design setup [2, 7, 8]. Likewise, simulation was applied to the injection blow molding. Schmidt [9] numerically simulated free blowing as well as stretch injection blow molding for polyethylene terephthalate (PET) bottles and compared it with actual experiments. They showed that simulation is capable of mimicking the injection blow molding, yet, improvements can be achieved with better understanding of the rheology of PET during the process. In another work, Pham et al [10] used a visco-hyperelastic model to describe the stretching behavior of PET bottles production, then a finite element formulation was developed to simulate the stretch blow molding process. The simulation provided good agreement with actual experiments with regard to the bottle thickness.

This study proposes a combined Taguchi-continuous simulation approach for improving the quality of injection blow molding. A case study from polyethylene (PE) bottles production is presented to demonstrate the implementation of the proposed approach.

The next three sections briefly introduce to the subjects of injection blow molding, Taguchi methods, and continuous simulation modeling, respectively. Section five describes the proposed approach. Implementation results are presented and analyzed in the penultimate section. In the concluding section, the principal findings of the research are stated.

II. Injection Blow Molding

Molding is the most common method for polymers' forming. The several molding techniques include injection, extrusion, blow, and compression molding. Polymers bottles can be produced either by extrusion blow molding or injection blow molding with superior dimensional and visual quality and wider applicability for the former process. Injection blow molding for producing plastic bottles can be divided into three steps: injection, blowing, and ejection.

An injection blow molding machine consists mainly of an extruder barrel, screw, and molding assembly. The polymers resin with suitable additives is fed from a hopper into a heated barrel to melt and form a viscous liquid. The hot melt is then injected, by a hydrostatic plunger, through nozzles into a hollow heated mold where it is conformed to the external shape of the mold cavity and is clamped around a mandrel to form the internal shape of the mold. The result is a thick tube of polymer. Fig. 1 is cross section schematic of an injection step.

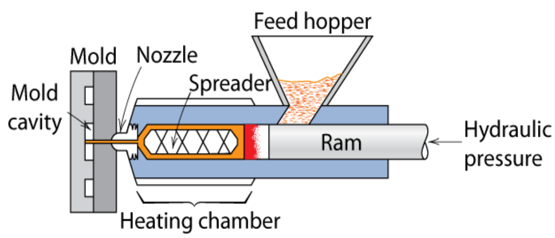


Fig. 1. Injection molding, [11]

In the blowing step the mold opens and the mandrel rotates and clamps into a hollow, chilled blow (battle) mold. Then, the mandrel opens and allows compressed air into the polymer tube, which inflates it to the required bottle shape. After some cooling time the blow mold opens and the mandrel rotates to the ejection position where the finished bottle is stripped off the mandrel. The blow mold can have many cavities depending on the bottle size and other features. Fig. 2 represents the blowing and ejections steps of the process with an example of three bottles cavities.

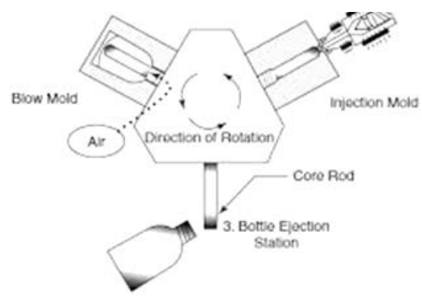


Fig. 2. Blowing and ejection process steps, [12]

III. Taguchi Method

Taguchi method or Taguchi experimental designs are fractional factorial designs with large screening. In addition to its new fractioning way, Taguchi method has introduced several innovative ways of conceptualizing an experiment including tolerance design and parameter design. Parameter design aims to have a robust product or process in the face of uncontrollable variation. To achieve this robustness, Taguchi proposed to use inner and outer array designs to consider the design factors and noise factors, respectively.

Taguchi method has several steps. First, the identification of the problem with its related causing factors, the interactions, and levels. Next, Taguchi method selects the appropriate (S/N) ratio for the quality characteristic of the studied product or process. 'Signal' represents the desirable output effect (mean) for the characteristic while 'noise' represents the undesirable effect (signal disturbance) due to external factors which are referred to by noise factors. Three ratio types can be used: 'Smaller-the-better', 'Nominal-the-best-, or 'Larger-the-better'. Later, the experimental design is determined and appropriate orthogonal array is selected, accordingly, the number of runs to be performed will be defined. Finally the results are analyzed and optimum settings for input factors are determined, thereafter, optimizing the studied response.

IV. CONTINUOUS SIMULATOIN MODELING

Simulation is the imitation of a system's operations over time. Simulation modeling consists of two main parts: 1) Model development, which is a representation of a system's key attributes and functions, and 2) Simulation, which is mimicking the actual system by running the model over a period of time. Often, computer experiments are used to run simulation models.

There are four types of simulation modeling, [13]: Discrete event simulation, agent-based simulation, continuous simulation, and hybrid simulation. Discrete event simulation models are a transaction-flow approach which use the main elements of entities, resources, and control elements. It is generally used in simulating the flow of material or information which can be described as moving in discrete steps or packets. Application examples for discrete event simulation include factory and warehouses operations. Agent-based simulation is a special class of discrete event simulation in which mobile entities do not just have attributes but also rules for interacting with each other.

Continuous simulation models are systems that are represented by differential equations. It solves these differential equations which describe the evolution of the system. Rather than moving in discrete steps, continuous simulation is appropriate for systems where the material or information flow can be described as evolving or moving continuously. For instance, simulation of fluids movement through pipes can most appropriately be represented using a continuous simulator. Hybrid simulation combines the features of discrete simulators and continuous simulators by solving differential equations with superimposing discrete events on the continuously varying system.

V. THE PROPOSED ALGORITHM

The suggested approach for solving the current problem is summarized by the flowchart represented in Fig. 3. First, the problem must be thoroughly defined and variables which are critical to solve the problem should be identified. In addition, the extent to which these variables need to be analyzed and measured should be determined. Tools which can be used in this step include process mapping tools, cause-and-effect matrix, Kano analysis, Pareto chart, etc. Afterward; the first step collects data regarding the critical to problem-solving variables. Once the problem is well defined, the second step simulates the process through continuous simulation using the data collected in the previous step. Next, the model is validated by comparing the simulated results with actual data. If not validated, the algorithm restarts from the first step, otherwise; Taguchi analysis/analyses is/are performed using the collected data from the first step if sufficient, else, the built simulated model is utilized to generate further data. Second to last, Taguchi results are validated through simulation and actual implementation. If not accepted the whole algorithm is repeated. Finally, the results are reported.

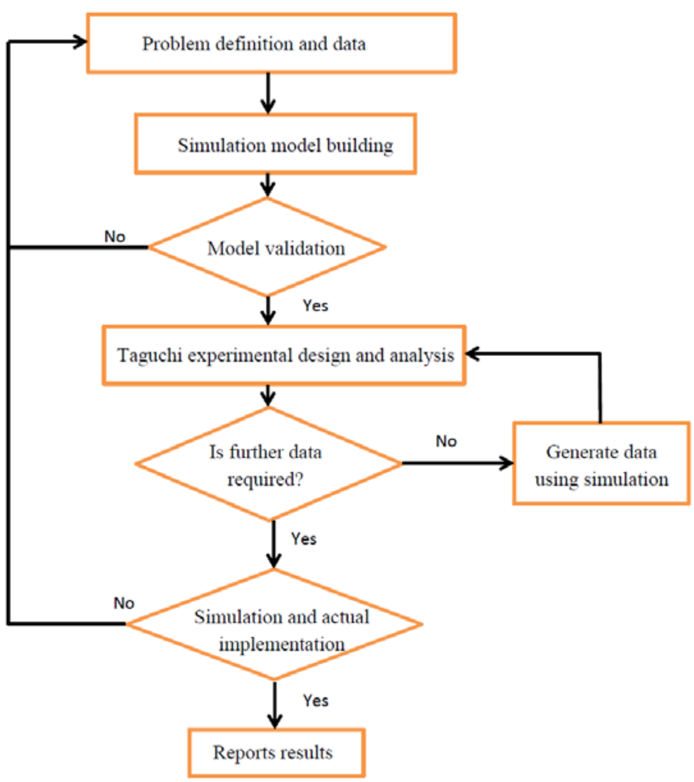


Fig. 3. Flowchart of the proposed algorithm

VI. IMPLEMENTATION EXAMPLE

This section demonstrates the implementation of the proposed algorithm. The approach was implemented in a Jordanian company which is specialized in the production of plastic packaging products for pharmaceutical, veterinary, and cosmetic industries. Since it was receiving the highest number of complaints, the injection blow molding process for producing a 100 ml PE bottle, a drug's bottle, was selected for the implementation.

A. Problem definition and data collection

Through initial investigation of customer complaints the complaints were clearly related to the defects in the production of the PE bottle. From records, three main defects were revealed: black spots, flash at the bottle's neck, and widening of the bottle bottom. Through several brainstorming with experts, causes and effects diagram for each of these defects were found. Table I summarizes the causes for these three main defects while Fig. 4 shows, as an example, a cause and effect diagram that was created for the "black spots" defect.

TABLE I. Main defects and their causes

Defect	Main causes
Black spots	Thermostat damage, high injection delay time, insufficient screw maintenance
Flash at the bottle's neck	Incorrect setting for the error water units temperature, damage in the mold, and inadequate compression of mold seal
Widening of the bottle bottom	High temperature of core tips and inadequate treatment.

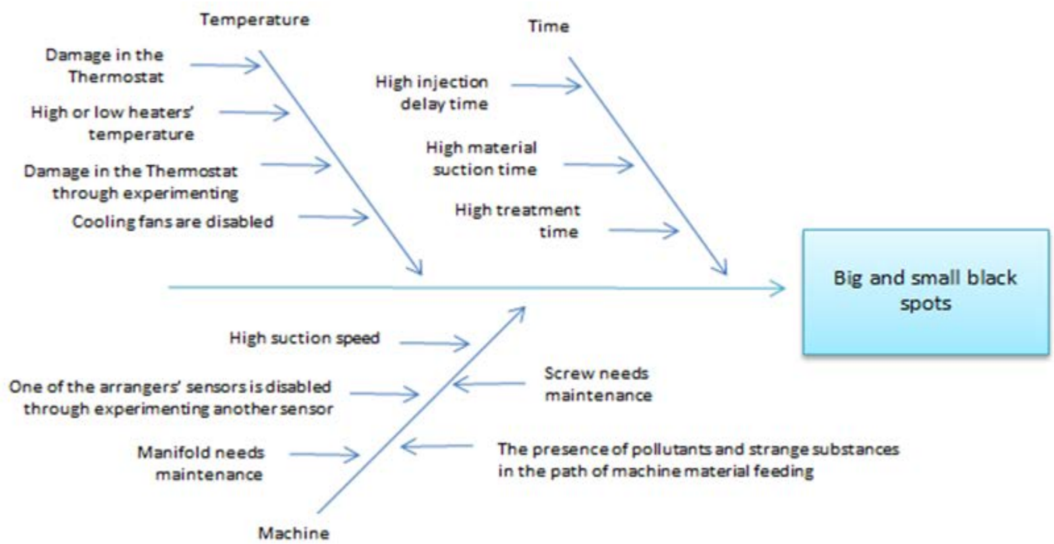


Fig. 4. Cause and effect diagram for the "black spots" defect

In order to have a comprehensive understanding for the factors affecting the injection blow molding process, experts were asked to answer the question of: What are the main parameters that affect this process. Also, plastics' injection molding handbooks and related machines' technical data were consulted to answer the same question. As a result, the most significant parameters which were found significant in affecting the injection blow molding process, and are usually calibrated when performing the process, were: the 'injection pressure', provided by the hydrostatic plunger; the 'cure time', the time during which the plastic resin is formed; the 'blow air delay', which is the time for compressed air to be blown in the tube; the 'melting temperature', which is the melting point of the resin as it goes through the process; the 'first blow air', the time for the first injection of air in the blow mold; and finally, the neck, center and bottom temperatures of the water that circulates around the mold at the neck, center and bottom positions; respectively. Table II provides the boundary levels for each of main parameters. As before, these levels were set in light of the data available in injection blow machine manuals, from the quality control department of the company where the case is implemented, and plastics injection molding handbooks.

TABLE II. Units and levels for the significant process parameters

Parameter	Low level	High level
Injection pressure (bar)	6.5	8
Cure time (sec)	4	6
Blow air delay (sec)	0.5	1.2
Melting temperature (°C)	195	230
First blow air (sec)	9	12
Neck mold temperature (°C)	70	85
Center mold temperature (°C)	98	105
Bottom mold temperature (°C)	45	80

After defining the process key parameters, operational data was collected for those eight parameters. Table III represents the data which was collected for twelve runs under different combination conditions of the eight parameters. At each run the number of produced bottles was recorded and the waste percentage, generated from total produced defective bottles, was calculated. It is noteworthy that the production runs in table III are ranked in ascending order with respect to waste percentage.

TABLE III. Collected data

Run	Key parameters and their levels								Bottles Produced	Waste (%)
	Inj. press.	***Cure time***	***Blow air delay***	***Melt. temp.***	***First blow air***	***Neck mold temp.***	***Center mold temp.***	***Bottom mold temp.***		
1	low	low	low	low	low	low	low	low	202,635	4.54
2	high	low	high	low	high	high	high	low	198,450	5.06
3	low	low	low	low	low	high	high	high	186,638	6.35
4	high	high	high	low	low	low	low	high	243,695	6.47
5	Low	high	low	high	high	low	high	high	222,456	7.31
6	High	high	low	low	high	low	high	low	187,345	8.24
7	high	high	low	high	low	high	low	low	200,324	8.95
8	High	low	high	high	low	low	high	high	234,980	10.41
9	low	high	high	High	low	high	high	low	198,765	12.81
10	low	high	high	low	high	high	low	high	212,987	18.35
11	Low	low	high	high	high	low	low	low	206,543	22.22
12	High	low	low	high	high	high	low	high	204,567	48.59

B. Building the continuous simulation model and its validation

Continuous simulation is clearly the appropriate simulation type to simulate the injection blow molding process since the process involves continuous material's movement. Autodesk® was selected to model and simulate the process. First, a 2D drawing of the bottle was generated. Then, this 2D was converted to a 3D drawing as given by Fig. 5. Next, the 3D drawing was exported to a mold design format that is required to cope with Autodesk® simulation mold flow adviser; which was used to conduct the actual simulation representing the final simulation modeling steps.

a) 2D

b) 3D

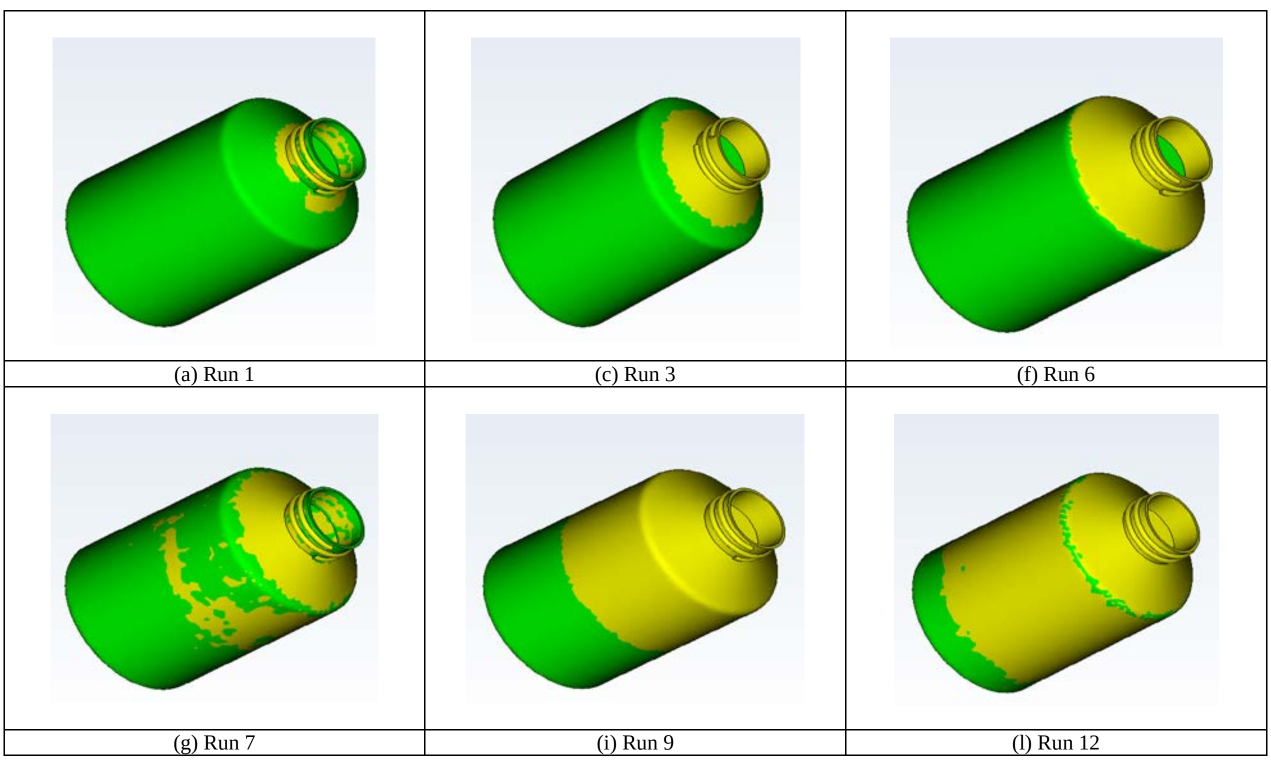
Fig. 5. 2D and 3D drawings for the 10 ml PE bottle (dimensions are in mm)

After building the simulation model it was used to simulate the injection blow molding process using the simulation mold flow adviser in Autodesk®. This advisor uses a three-level indicator, "high quality", "medium quality", and "low quality"; to evaluate its simulation. For example, if a simulation run has the perfect operational conditions; then the generated product "high quality" would be 100% and its "medium quality" and "low quality" would be 0%. As the "high quality" decreases the "medium quality" and "low quality" increases; consequently, the bottle would have a higher chance of being defective. Table IV provides the simulation results for the same conditions of the runs in table III. Only the "high quality" and "medium quality" levels of the evaluation indicator were resulted. In addition, there is a clear significant opposite/positive relation between the waste in the actual runs and the high quality/medium quality of the simulation model. These results in fact validate the appropriateness and fitness of the built simulation model.

TABLE IV. Autodesk® Simulation results

Run	Actual waste (%)	High simulated quality (%)	Medium simulated quality (%)
1	4.50	93.60	6.37
2	5.06	93.20	6.73
3	6.35	87.30	12.70
4	6.47	83.30	16.70
5	7.30	81.40	18.60
6	8.24	81.00	19.00
7	8.95	65.20	34.60
8	10.41	47.00	53.00
9	12.81	46.50	53.30
10	18.35	45.50	54.50
11	22.22	39.20	60.60
12	48.59	18.60	81.30

Fig. 6 displays a sample of the simulated bottles from the 12 runs mentioned in table III. Each bottle has a green (dark) and yellow (white) colors indicating the quality of the bottle. The green area represents the "high quality", that is, the plastic flow at that area is very much accepted with low probability of having a defect. On the other hand, the yellow color, for the "medium quality", implies higher defect occurring probability.



(a) Run 1 (c) Run 3 (f) Run 6

(g) Run 7 (i) Run 9 (l) Run 12

Fig. 6. Sample of the simulated bottles using Autodesk®

C. *Taguchi experimental design and analysis*

This section explains the steps of implementing the Taguchi method. Where required, Minitab was used for the experimental design and analysis. The steps are as follows:

1) Selection of the process parameters and their levels:

The same parameters and levels given in table II were utilized.

2) Selection of orthogonal array with its runs and the S/N ratio:

Since the studied case has eight parameters each with two levels, the L12 orthogonal array was used. The 12 runs for the L12 array with different parameters levels combinations were generated. Those runs were identical to what is given in table III. Finally, since the aim is to reduce the waste percentage; the 'Smaller-the-Better' was selected for the S/N ratio.

3) Calculating the S/N ratio:

Table V shows the calculated S/N ratio for the 12 runs. It is obvious from the calculations that as the output (waste %) decreases the S/N also decreases.

TABLE V. S/N ratio for the 12 runs

Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Waste	4.5	5.06	6.35	6.47	7.3	8.24	8.95	10.41	12.81	18.35	22.22	48.59
S/N	-13.14	-14.08	-16.06	-16.22	-16.81	-17.28	-18.32	-19.04	-22.15	-25.36	-26.94	-33.73

4) Finding the parameters' optimal levels with their ranking:

Fig. 7 shows the main effect plot for the S/N ratios. From the Fig. the optimal levels for the eight parameters, in descending ranking starting from the most important, can be determined as: 105 °C for the center mold temperature, 9 seconds for the first blow air, 195 °C for the melting temperature, 0.5 seconds for the blow air delay, 70 °C for the neck mold temperature, 6 seconds for the cure time, 45 °C for the bottom mold temperature, and 8 bars for the injection pressure.

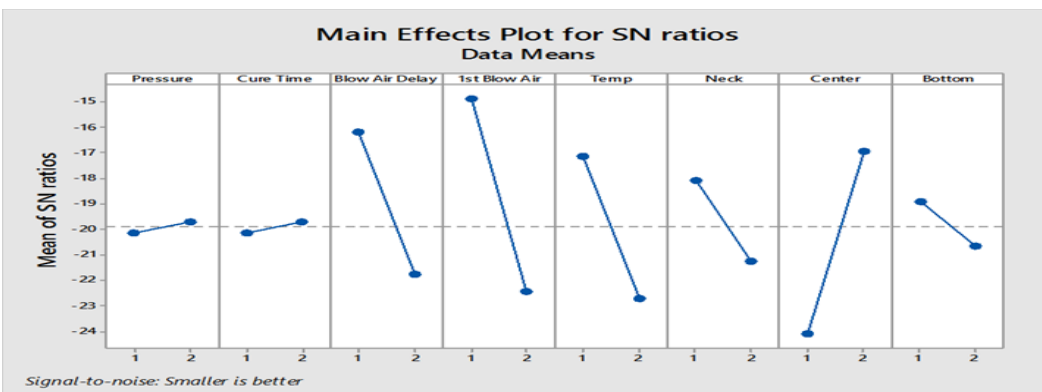


Fig. 7. Main effects plot for S/N ratios

D. *Results validation*

To validate the results of the previous step, the built simulation model was run under the recommended parameters values. The results of this run produced a bottle with 99.2% "high quality" which is 5.6% better than the best previous quality level. In other words, and through using regression analysis, the 99.2% is equivalent to 0.32% waste which is way lower than the lowest previous waste of 4.54%. This result is a clear validation for the proposed algorithm.

VII. CONCLUSIONS

In the present work, the optimal operational parameters for an injection blow molding process has been developed using the Taguchi experimental design approach supported by continuous simulation modeling. The proposed approach has been applied to the injection blow molding process of a PE drug bottle. The optimal operational parameters have been determined by analyzing the Taguchi results statistically. Then, these parameters settings were validated through simulation confirmation experiments. As a result, the waste percentage was reduced from 4.54% to 0.32%. It is thus concluded that the proposed approach can be successfully reflected in the selection of the operational parameters of industrial injection blow molding processes.

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BIOGRAPHY

Safwan A. Altarazi is a dynamic experienced professor, trainer, researcher, and consultant with a strong record of achievements in the fields of quality management and supply chain management. Have more than ten years of experience in academia-industry bridging projects. Rigid problem solving capability across different fields in very systematic manner. Have raised about $250,000 as research funds during the last six years (more than $100,000 as principal researcher). Have participated in two EU-Tempus projects for developing master programs in various engineering fields. Served in various administrative positions including head of industrial engineering department-Germany Jordanian University, head of maintenance engineering and management department-Germany Jordanian University, elected member of mechanical engineering assembly board-Jordanian Engineers Association, chair of scientific committee-Seventh Jordanian International Mechanical Engineering Conference (JIMEC2010), and chair of the first International Conference on Industrial, Systems and Manufacturing Engineering (ISME’14.)

Gazal Al Soudani Jordanian born in August 1991. She graduated from Al Mashrek International School in Amman with the highest GPA of her class. She later received her Bachelor's degree in Industrial Engineering and Management Systems from the German Jordanian University in September 2014 on a scholarship of academic excellence. As a part of her undergraduate program, Gazal studied one semester in Fachhochschule Koeln in Germany, after which she did a 6-month internship working at Unify GmbH in Munich - Germany. Upon graduation, with her colleagues she conducted the project “A Taguchi-Continuous Simulation Approach to the Injection Molding Blowing Process Quality Improvement” that is being presented."

Zina O. Karadsheh was student council president for two years in a row, graduated from school with honors and is soon to be a graduate from the German Jordanian University, where she was also a co-finder of a club called “Lab-On-Wheels” that aims to help bring hands-on experiments to children studying in rural areas in Amman, Jordan. Moreover, she did an internship in the development of Prototype Vans for one year in one of the worlds most recognized companies, Daimler AG.