



## INTRODUCTION

Experimental design techniques emerged in England during the 1920s. R.A. Fisher led initial applications in the field of agriculture [1]. Other notable contributors to this body of knowledge over the years include Rao, Plackett, Burman, Box, Taguchi, Barker, Derringer, Hunter, John, Myers, Montgomery, Cornell and numerous others. Until the early 1980s, most industrial experiments were set up and analyzed by specialists within an organization. Today, with the advent of readily available software, the non-statistical person can successfully set up and analyze simple but powerful experiments.

A designed experiment is a well-controlled family of tests. Each test is run one or more times. For each controlled test, outputs, also known as responses, are measured. From test to test controlled changes will be made. Once the tests are completed, the data can be analyzed. As you will see, simple graphs can be of great value in furthering our understanding of the results of the experiment. As the data is analyzed, conclusions will be reached as to the best setting for the inputs, or factors. The final step is to actually try these best settings and see if they produce the predicted results from the analysis. If the results are close to the prediction, and better than any baseline we might have, the experiment will be declared a success.

Let's jump right into an example that shows the power of using design of experiments. In our example, we want to manufacture the "perfect" Lego®.



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Suppose Legos are being injection-molded in a single cavity tool, one part at a time. The response, or output, we are interested in is the outside length of the part. We want our "perfect" Lego® to have an outside length of 57.3 mm. Our process knowledge tells us that two factors affect the length: Fill Speed and Hold Pressure. We want to know what happens to the length as we vary Fill Speed from 2 inches per second to 5 inches per second and Hold Pressure from 4600 psi to 6500 psi. The 2 and 5 inches per second for Fill Speed are just different set points, commonly referred to as levels. The manufacturer would like to fill as fast as possible in order to have a shorter cycle time. Five shots (five parts in this case) were made at each run. Table 1 shows the initial set-up for this experiment.

**Table 1**

Run	Fill Speed	Hold Pressure	Outside Length (1st Shot)	Outside Length (2nd Shot)	Outside Length (3rd Shot)	Outside Length (4th Shot)	Outside Length (5th Shot)
1	2	4600					
2	2	6500					
3	5	4600					
4	5	6500					

As the above table shows, four unique tests, or runs, were conducted. For run number 1, the Fill Speed was set at 2 inches per second and the Hold Pressure was set at 4600 psi. Ince the process had reached steady state, five shots were completed. The outside length was measured on all five parts and recorded in Table 1 - Run 1.

**Table 1 - Run 1**

Run	Fill Speed	Hold Pressure	Outside Length (1st Shot)	Outside Length (2nd Shot)	Outside Length (3rd Shot)	Outside Length (4th Shot)	Outside Length (5th Shot)
1	2	4600	56.5	56.4	56.4	56.5	56.4
2	2	6500					
3	5	4600					
4	5	6500					

For run #2, the fill speed was held at 2 inches per second and the Hold Pressure was set to 6500 psi. No other changes were made. Again, samples were taken after a steady state for the process was reached. The outside length was measured on all five parts and recorded in Table 1 - Run 2.

Table 1 - Run 2

Run	Fill Speed	Hold Pressure	Outside Length (1st Shot)	Outside Length (2nd Shot)	Outside Length (3rd Shot)	Outside Length (4th Shot)	Outside Length (5th Shot)
1	2	4600	56.5	56.4	56.4	56.5	56.4
2	2	6500	57.9	57.9	57.9	58.0	57.9
3	5	4600					
4	5	6500					

Runs 3 and 4 were completed in a similar manner. The results are shown in Table 1 – All.

Table 1 - All

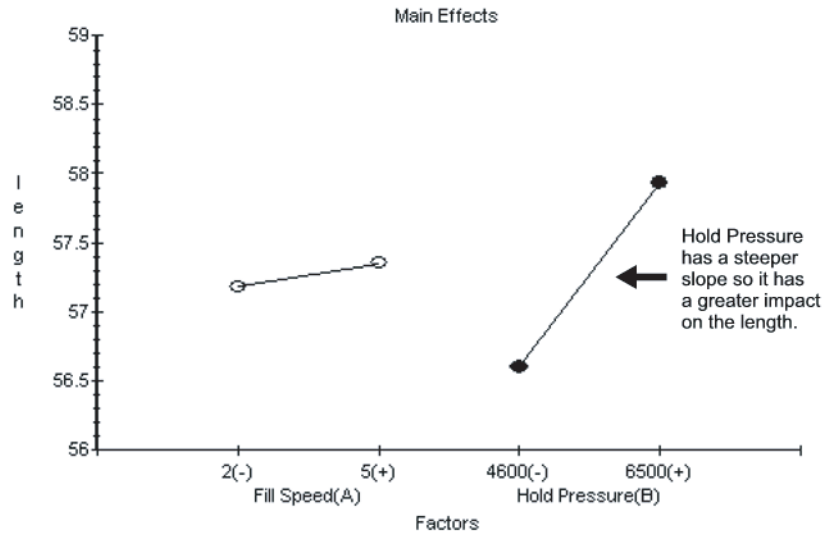
Run	Fill Speed	Hold Pressure	Outside Length (1st Shot)	Outside Length (2nd Shot)	Outside Length (3rd Shot)	Outside Length (4th Shot)	Outside Length (5th Shot)
1	2	4600	58.5	58.1	58.1	58.5	58.1
2	2	6500	57.9	57.9	57.9	58.0	57.9
3	5	4600	58.7	58.7	58.8	58.8	58.8
4	5	6500	57.9	58.0	57.9	58.0	57.9

Using the data from the designed experiment, graphical analysis is now performed. In many cases, much of what is to be learned from an experiment can be gleaned from a few simple graphs. Let's learn about a couple of our favorites.

We refer to the chart shown in Figure 1 as a main effects plot. (Note the Y-axis is the response (length) and the X-axis plots level averages for each of the factors. By glancing at this chart, we can quickly learn the following:

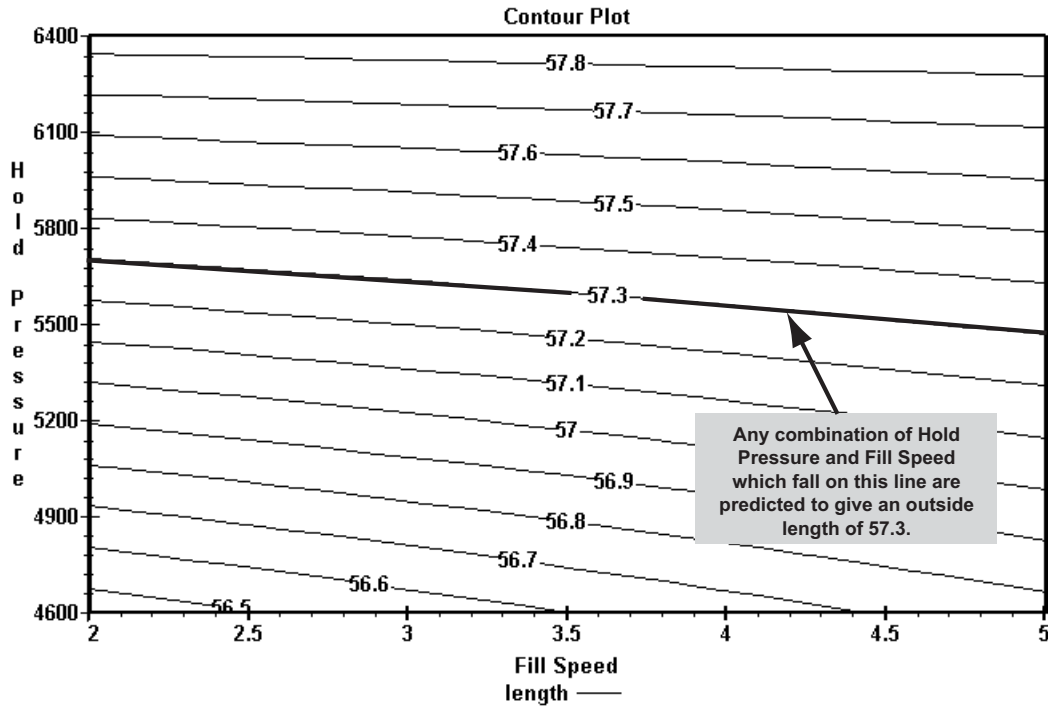
- ✓ Hold Pressure has a greater impact on the response than Fill Speed (the steeper the slope, the greater the impact).
- ✓ The effect (impact on change in response) of each factor is proportional (increase in setting increases the response).
- ✓ If our goal were to make the response greater, the high set point (fill speed at 5 inches per second, hold pressure at 6500 psi) for each factor appears best. If the goal were to decrease the response, slower speed and lower pressure are best.

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**Figure 1**

We don't want to minimize or maximize the length of our Lego®, we want it to measure exactly 57.3 mm. An important graphic that will help us achieve this goal is the contour plot shown in Figure 2. As we will learn later, the software builds a mathematical model based upon the data from the experiment to create this visualization.



**Figure 2**

In the contour graph, Hold Pressure is plotted on the Y-axis and Fill Speed is plotted on the X-axis. The response (outside length) is displayed as contour lines in the graph. This graph can help us predict how to hit a target value of 57.3. The contour plot predicts that any combination of Hold Pressure and Fill Speed that falls on the line labeled 57.3 will produce this value.

For example, if Fill Speed is set at 3.5 inches per second, then it is necessary to set the Hold Pressure at about 5600 psi to obtain a target dimension of 57.3. See Figure 3. Although this combination of settings was not actually run during your experiment, the contour plot was able to help predict that this combination of Fill Speed and Hold Pressure would produce a part that is 57.3 mm long.

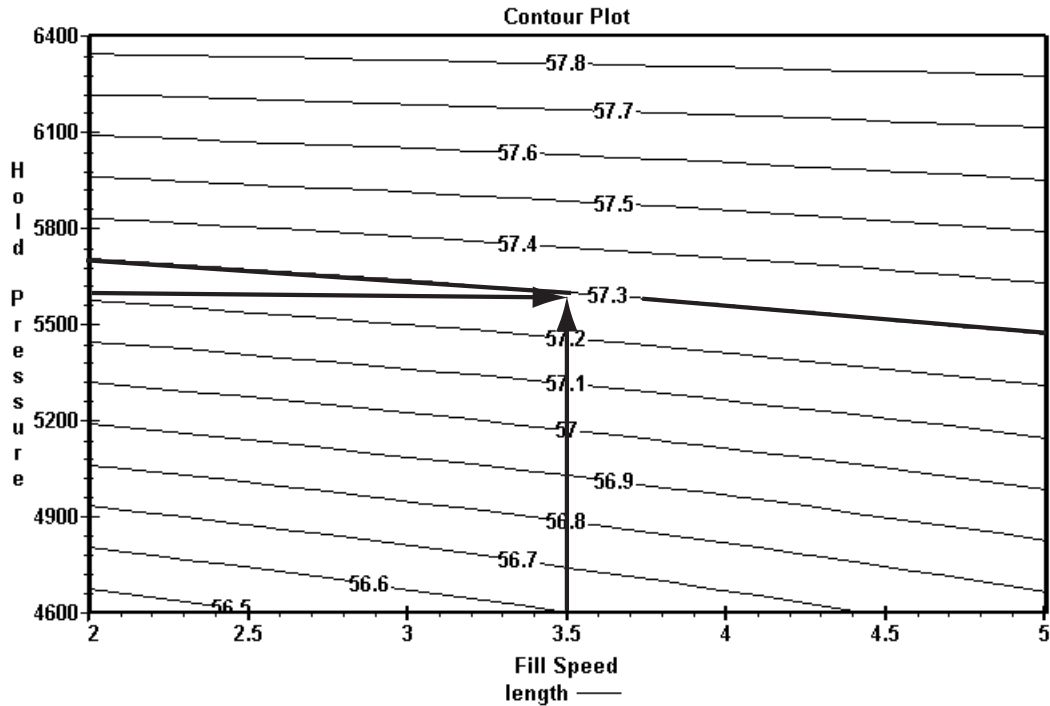
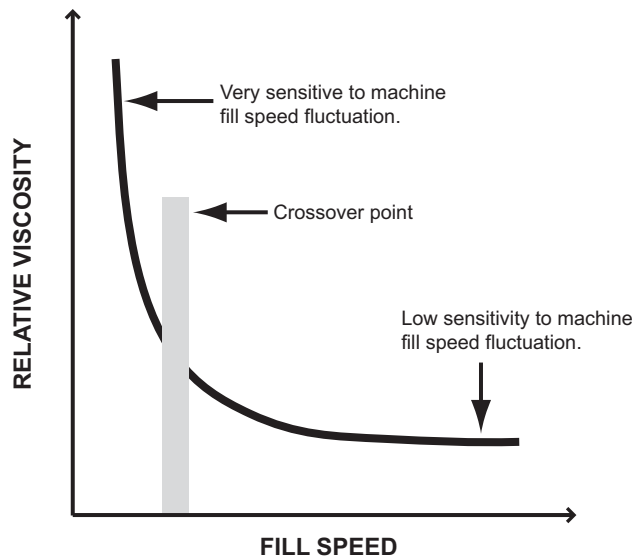


Figure 3

That's it. If you can read the preceding graphs, you are well on your way to conducting simple but powerful analysis of your experimental data. In later chapters we will go through the details of how these graphs are created. We will also provide several more powerful analysis tools.

Before leaving this simple experimental design example, it is important to note that we needed to know **something** about the technology being studied before attempting an experiment! For the Lego example, in order to inject the raw plastic pellets into the mold, the material needed to be melted. This implies knowledge of the recommended processing temperature of the thermoplastic (melt range recommended by the resin supplier). Molders control this by barrel zone heater control and shear heating. The experiment assumes the melt temperature is constant from shot to shot. If the material is overheated it can degrade. Degradation manifests itself in several key ways.

In practice, we cannot afford to be cavalier about the selection of levels for the factors. For example, the fill speed setting must be within the capability of the machine. Additionally, it needs to be in the proper range for the process. Fundamental to this is the relative viscosity of the material. Unlike water, the viscosity of plastic varies dramatically with injection velocity. Unfortunately, the shape of this curve varies dramatically with resin type, loadings, machine, runner, gates, etc. Each machine/resin/tool combination needs to be characterized. Fortunately, this is easy to do [2]. A typical viscosity vs. flow rate curve is shown in Figure 4.



**Figure 4**

At “slow” speeds, the plastic is being injected at a point where viscosity can change dramatically due to batch-to-batch differences or lack of machine repeatability. At “fast” speeds the viscosity of the plastic is much more consistent. Pick levels in your experiment for the fill speed where the curve has flattened out.

As you will see, good experimental design requires solid knowledge of the technology in order to obtain meaningful results. Unfortunately, some books, seminars, and articles on experimental design miss this point. The more you know about the technology being studied, the more useful your experiments will be.

## **Introduction Bibliography**

1. "J. Agri. Sci., (13), R.A. Fisher
2. *Injection Molding magazine*, Oct. 1997 three part series on Scientific Molding
3. RJG Inc., is an Injection Molding consulting firm in Traverse City, Michigan