

Example 2: Bearing Dimensions

The previous example, for liner curl, showed how one output characteristic of a manufactured product was optimized. This example illustrates how to concurrently deal with multiple characteristics on a single product.

Product Description

The product in this example is a Teflon-lined, metal-backed bearing illustrated in the photo below. The bearing is die formed in a high-speed manufacturing process.

Problem Background

This product has three primary dimensional characteristics: outside diameter, inside diameter, and length. The manufacturer's goal was the elimination of scrap, rework, and customer returns, the minimization of setup times and tool sets, improved targeting, and reduced variation. (We will limit this presentation to the optimization of the three primary dimensional characteristics.)

Since operators had to concurrently deal with three dimensional characteristics, process designers had provided a range of tooling for each bearing design. Specifically, machine operators were equipped with 5 OD tools, 7 ID tools, and had the ability to alter the length of the material input "blank" in at least 10 unique increments. Given these conditions, the operators had 350 different ways to set up and run the manufacturing process for a specific bearing ($5 \times 7 \times 10 = 350$).



Detail of Problem Solution

The group formed to perform the experiment decided to investigate only the three primary input factors for bearing formation: the OD tool (die), the ID tool (mandrel), and the blank length (the flat stock fed into the forming press). They also wanted to determine if there was any interaction between any of these input factors during the forming process.

An abbreviated version of the array for this optimization effort is shown below. The AB, AC, BC, and ABC columns were “empty” and reserved for analysis of input factor interactions. If these interactions existed, they would plot on response graphs as significant effects.

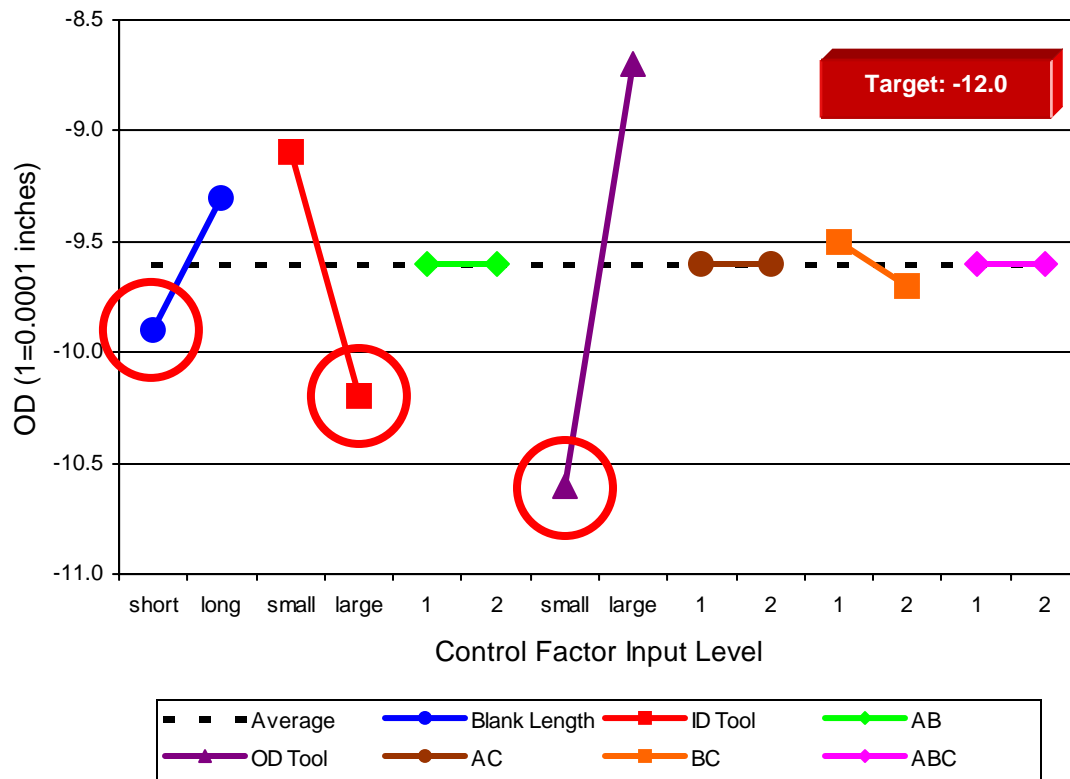
Sample bearings were measured for all three characteristics being studied and the average results are shown in the array. Note that the OD and the ID were both measured as deviations from a setting standard.

Trial	Inputs							Average Results		
	A Blank Length	B ID Tool	AB	C OD Tool	AC	BC	ABC	OD 1=0.0001”	ID 1=0.0001”	Length 1=1.000”
1	short	small	1	small	1	1	1	-10.2	10.8	.5894
2	short	small	1	large	2	2	2	-8.5	9.5	.5881
3	short	large	2	small	1	2	2	-11.5	15.2	.5910
4	short	large	2	large	2	1	1	-9.4	13.1	.5894
5	long	small	2	small	2	1	2	-9.6	9.7	.5910
6	long	small	2	large	1	2	1	-7.9	8.8	.5900
7	long	large	1	small	2	2	1	-10.9	13.9	.5929
8	long	large	1	large	1	1	2	-8.9	12.8	.5920

In order to investigate the contributions that each input/level makes to the variation of each dimensional characteristic, the average SNR was calculated for each trial and each characteristic. These results are tabulated below:

Trial	Inputs							Signal-to-Noise Ratios (dB)		
	A Blank Length	B ID Tool	AB	C OD Tool	AC	BC	ABC	OD	ID	Length 1=1.000”
1	short	small	1	small	1	1	1	3.34	15.63	52.24
2	short	small	1	large	2	2	2	-1.30	11.12	51.57
3	short	large	2	small	1	2	2	8.89	24.16	48.26
4	short	large	2	large	2	1	1	5.49	20.38	48.69
5	long	small	2	small	2	1	2	2.01	13.36	53.26
6	long	small	2	large	1	2	1	-0.56	10.97	52.26
7	long	large	1	small	2	2	1	8.26	18.58	47.41
8	long	large	1	large	1	1	2	8.64	19.51	47.89

Outside Diameter Response Graph



The response graph of bearing outside diameter targeting is shown above. The only factors that had a large effect on the bearing outside diameter were the three inputs chosen for experimentation. The four “interaction” effects all proved to have no significant impact on bearing outside diameter. In other words, there were no significant interactions between the input factors evaluated.

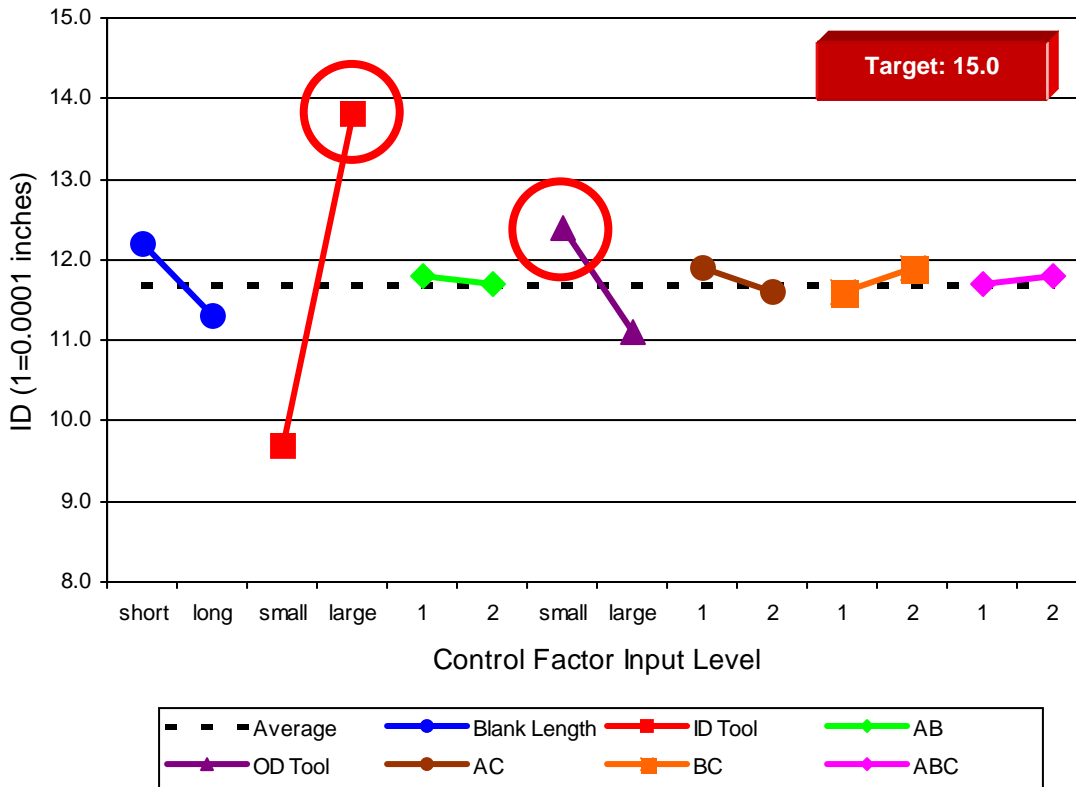
The average outside diameter measured during the course of this experiment was -0.00096 inches, while the engineering specification for this characteristic required a target value of -0.00120 inches. The red circles illustrate the factor levels (significant factors only) that had to be chosen to target the bearing OD as close as possible to the specification value. The predicted OD response for the optimized process was calculated as shown below (1=0.0001 inches):

$$OD Ave_{pred} \approx -9.6 + (-9.9 - (-9.6)) + (-10.2 - (-9.6)) + (-10.6 - (-9.6))$$

$$OD Ave_{pred} \approx -9.6 - 0.3 - 0.6 - 1.0$$

$$OD Ave_{pred} \approx -11.5$$

Inside Diameter Response Graph



As was the case with the outside diameter, there were no significant interactions between inputs that impacted the bearing inside diameter. This was good news for the manufacturer, as line operators and setup personnel can readily grasp how to alter product dimensions by changing forming tools or input material volumes. It is quite a bit more difficult, however, to establish protocols for line operators to control a process via interactions.

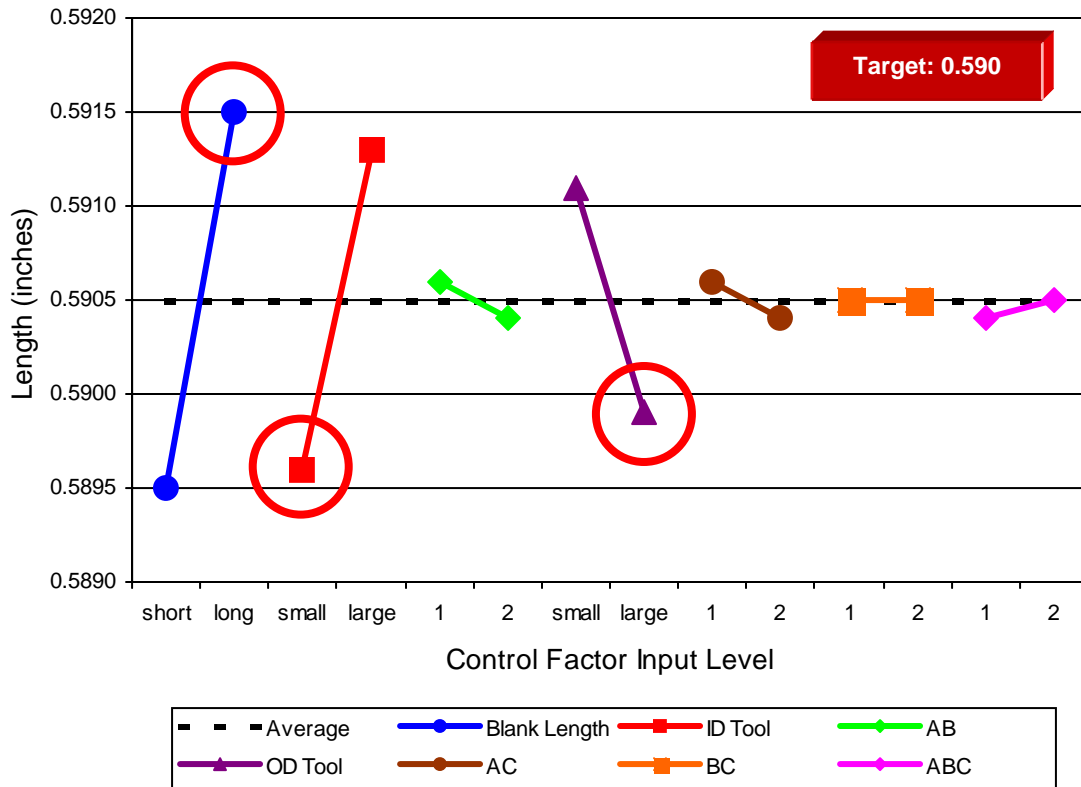
The engineering specification for inside diameter indicated a desired value of 0.0015 inches (measured as a deviation from a setting standard). The predicted response, using the two significant factors chosen above, was (1=0.0001 inches):

$$ID Ave_{pred} \approx 11.7 + (13.8 - 11.7) + (12.4 - 11.7)$$

$$ID Ave_{pred} \approx 11.5 + 2.1 + 0.7$$

$$ID Ave_{pred} \approx 14.3$$

Length Response Graph



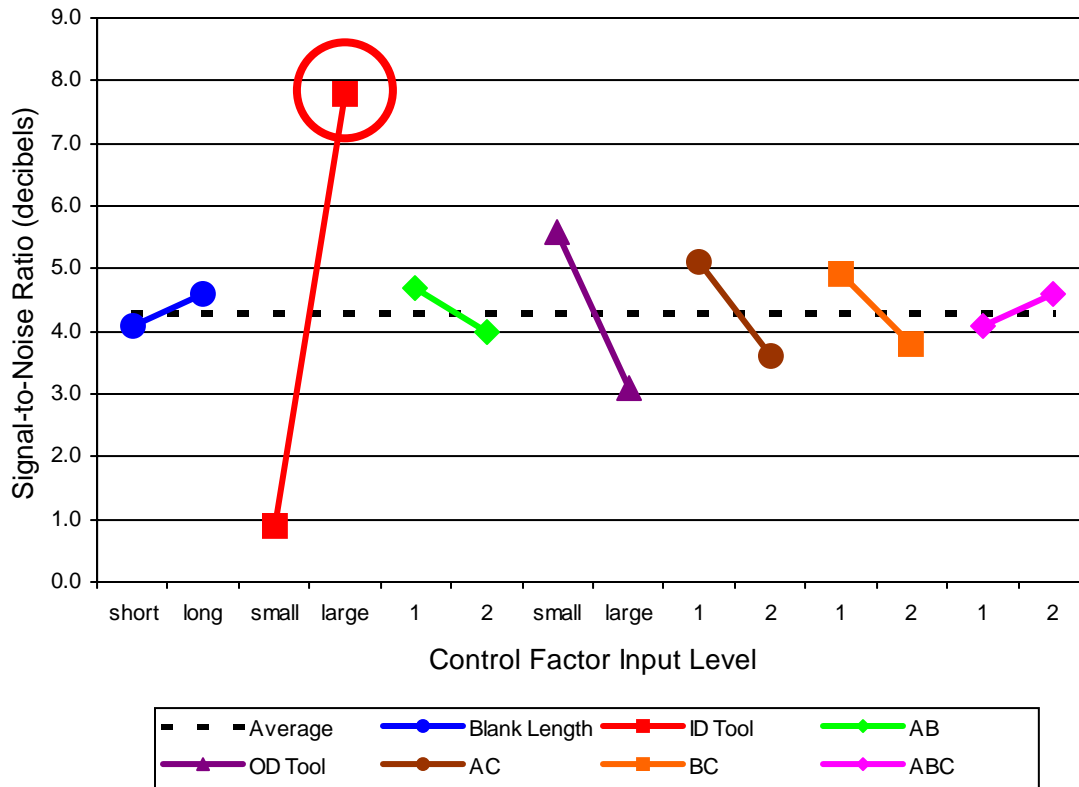
The length response graph above illustrates one of the most versatile aspects of optimization efforts via designed experimentation. The blueprint specified a target value of 0.590 inches. To obtain an average result as close to this value as possible, factors and levels could be chosen to pull the average output of the process down or up as needed. For this example, the long blank length tended to pull the average up, while the small ID tool pulled it down. These two effects virtually negated one another, allowing the use of the large OD tool to target the optimized bearing length precisely at 0.590 inches.

$$Length Ave_{pred} \approx 0.5905 + (0.5915 - 0.5905) + (0.5896 - 0.5905) + (0.5899 - 0.5905)$$

$$Length Ave_{pred} \approx 0.5905 + 0.0010 - 0.0009 - 0.0006$$

$$Length Ave_{pred} \approx 0.590 \text{ inches}$$

Outside Diameter Signal-to-Noise Ratio



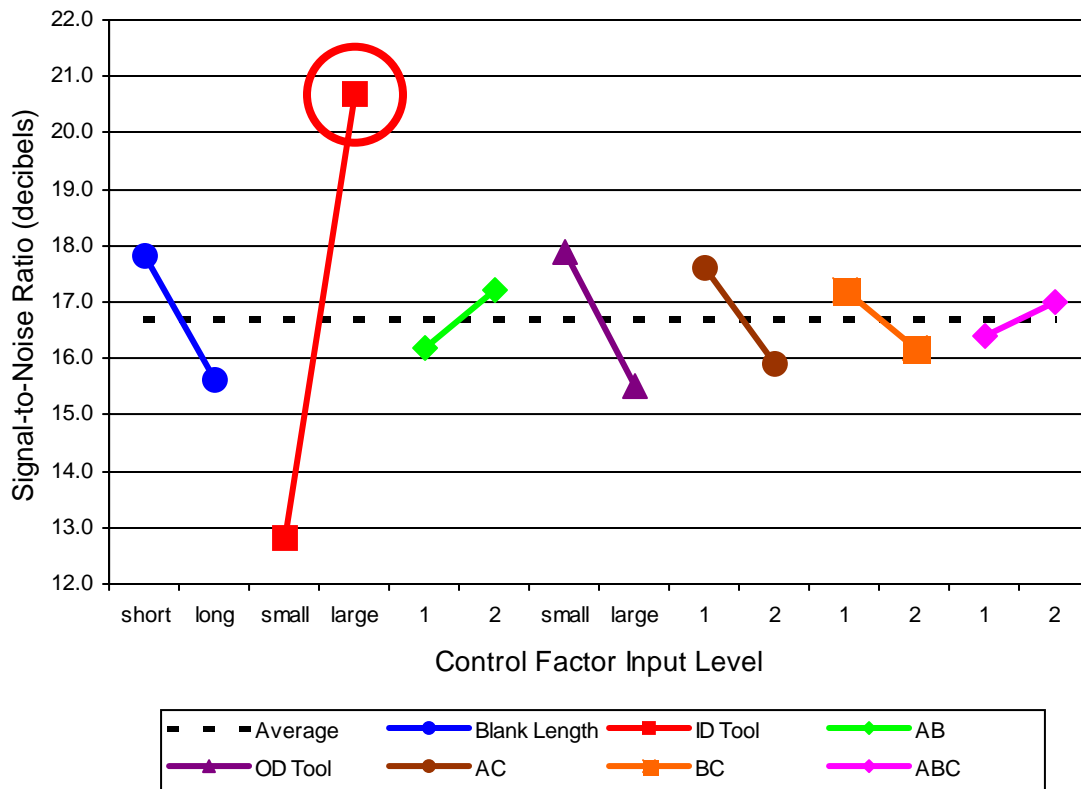
Considering only the factor and level which had the most significant impact on signal-to-noise ratio (i.e., variation), the manufacturer chose the large ID tool to minimize the variation in the bearing outside diameter. This was certainly an unexpected result – prior to this experiment none of the manufacturing personnel would have imagined that the proper selection of the ID tool would minimize the variability of the OD response. The predicted signal-to-noise ratio for the OD response under these conditions was:

$$OD SNR_{pred} \approx 4.3 + (7.8 - 4.3)$$

$$OD SNR_{pred} \approx 4.3 + 3.5$$

$$OD SNR_{pred} \approx 7.8 \text{ decibels}$$

Inside Diameter Signal-to-Noise Ratio



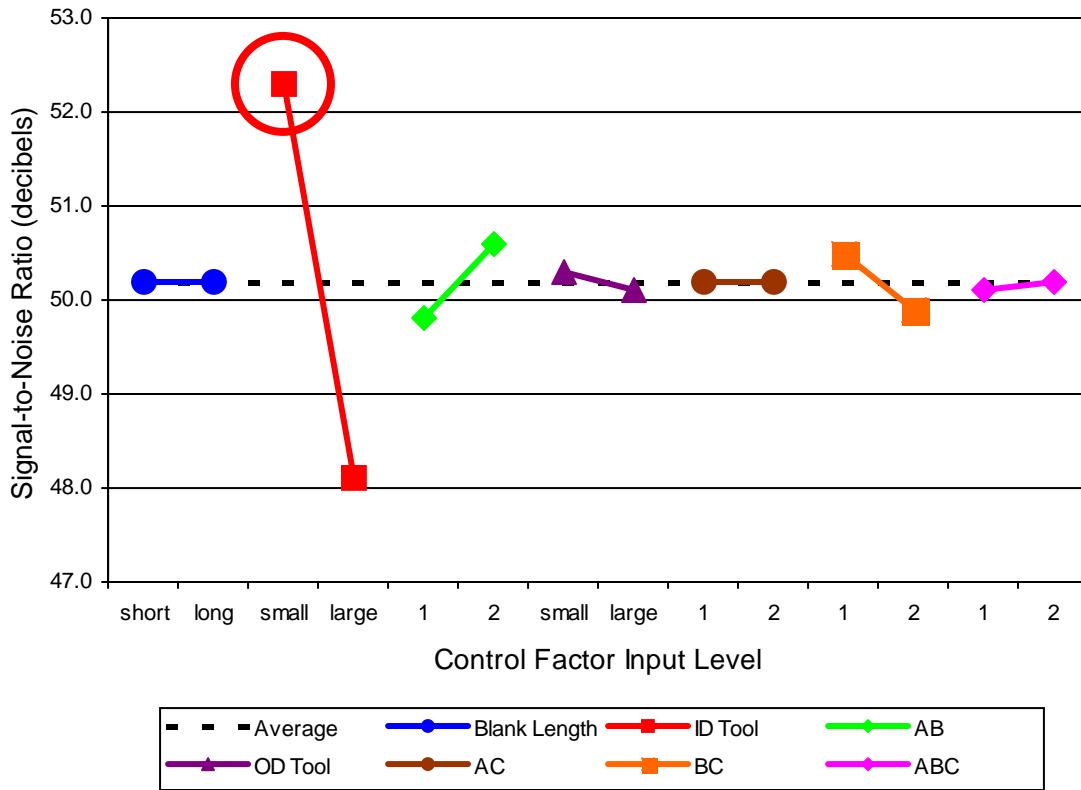
The selection of the inside diameter tool also controlled the amount of variation in the bearing ID response. This factor was not unexpected. Manufacturing personnel could readily understand that the amount of work imparted to the raw material by the ID tool would control the variation of the ID characteristic. The predicted optimum signal-to-noise ratio of the ID response was:

$$ID\ SNR_{pred} \approx 16.7 + (20.7 - 16.7)$$

$$ID\ SNR_{pred} \approx 16.7 + 4.0$$

$$ID\ SNR_{pred} \approx 20.7\ \text{decibels}$$

Length Signal-to-Noise Ratio



The variability of the bearing length was also controlled by the choice of the ID tool size. Like the variability of the OD, this result was somewhat surprising, especially since the ID tool was the only one that had any significant effect on the length variability. Notice that both the blank length and the OD tool had no significant effect on length variability. The predicted optimum signal-to-noise ratio for bearing length was:

$$ID\ SNR_{pred} \approx 50.2 + (52.3 - 50.2)$$

$$ID\ SNR_{pred} \approx 50.2 + 2.1$$

$$ID\ SNR_{pred} \approx 52.3\ \text{decibels}$$

After completion of the response graphs for averages and signal-to-noise ratios the manufacturer was ready to tabulate all of the results. Obviously, the hope was to optimize as many of the targets and variation levels as possible. The “multiple response” table below includes color-coding to highlight the conflicts found in each factor column.

Process Input Levels								
Response Category	Goal	A Blank Length	B ID Tool	AB	C OD Tool	AC	BC	ABC
OD Average	-0.0012	short	large	-	small	-	-	-
ID Average	0.0015	-	large	-	small	-	-	-
Length Average	0.590	long	small	-	large	-	-	-
OD Variation	↓	-	large	-	-	-	-	-
ID Variation	↓	-	large	-	-	-	-	-
Length Variation	↓	-	small	-	-	-	-	-
Optimized Response		short	large		small	-	-	

It was immediately evident that not all response categories could be optimized concurrently. The manufacturer needed to choose which responses were the most critical for an optimum product.

With few exceptions, the bearing outside and inside diameters were critical parameters to ensure product performance and longevity. The length was important only to the extent that the bearing “fit” in an individual application. Armed with this knowledge, the manufacturer was able to work with customers on a case-by-case basis to specify product dimensions that would take advantage of the relationships shown in the table above. In many instances, superior products were possible if the customer could tolerate a slightly larger tolerance on the bearing length.

All of these relationships were verified in confirmation runs for this experiment. Subsequent experimentation on this manufacturing process revealed a fourth factor that also impacted the characteristics shown. These efforts enabled the manufacturer to reduce tooling inventories and setup times on all bearing sizes made by this manufacturing process.