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Quality Quandaries*: The Case of Premature Drill Wear Out

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Quality Quandaries*: The Case of Premature Drill Wear Out

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INTRODUCTION

This problem occurred in a machining process for large casted metal parts. These parts are processed (by means of drilling, milling, and tapping) in a newly built production line, consisting of 21 coupled workstations, without large buffers between the stations. This lack of significant buffer capacity implicates that any disturbance in the line has a direct impact on the line output. The initial idea behind the set up of the production line was that production would run for 7.5 hours and then the tools (such as the drills) would be replaced in order to start again in a new shift.

The function of the machining process is to drill seven deep holes in the metal parts. The production line processes about 80 parts per shift. The performance of the drills is continually monitored by an automated system, which measures the energy consumed by the drills (torque). The purpose of this monitoring system is to prevent the drills from breaking.

The process suffered from frequent stoppages forced by the process monitoring system whenever it signaled an imminent drill break. Upon stopping the line, suspect drills would be replaced. The consequences of these frequent out-of-control signals included excessive downtime of the line (overall equipment efficiency [OEE] below 60%) and replacement of drills well before their specified life span.

A team of engineers and operators investigated the problem. Before designing a remedy, they first focused on establishing the root cause. Below we describe the team's actions and analyses, illustrating an important lesson for diagnostic problem solving. This lesson could be summarized as follows: before trying to discover a problem's cause by experiments involving detailed candidate causes, it is important first to achieve focus; that is, to narrow down the search space to a compact area. Note: For confidentiality reasons, some of the details and data sets have been modified, but care has been taken to leave the line of reasoning and the conclusions intact.

FIRST ATTEMPT AT SOLVING THE PROBLEM: BRAINSTORMING AND DESIGN OF EXPERIMENTS

As a first attempt at tackling this problem, a team of engineers and operators held a brainstorming meeting, generating ideas about possible causes of the frequent out-of-control signals that the process suffered from. The

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meeting produced about 40 conjectured causes, most of them relatively general, such as:

- Tool geometry
- Process feed and speed
- Tool coating
- Process tool setup
- Operator tool handling

The team wanted to use statistically designed experiments to figure out which of the hypothesized causes were the ones that truly affected premature drill wear out. To reduce the long list to a manageable size, the team scored each of the ideas by a voting process. Unfortunately, this voting process did not produce a strong focus; the Pareto chart of the potential causes sorted by voting score is relatively flat (see Figure 1).

The team decided to focus on the 15 causes having the highest scores, hoping to single out the few true causes by experimentation. On second thought, this plan turned out to be infeasible; experiments proved to be time consuming, especially given the large number of factors. A resolution IV fractional factorial experiment would require a minimum of 32 trials (namely, the 32-run 2^{15-10} design). In addition, in running such experiments the team faced practical problems that it did not know how to solve. The team did not know, for instance, how to determine the high and low levels for vague and unspecific parameters such as machine stiffness or operator tool handling. The team was stuck.

ACHIEVING FOCUS

The team realized that it needed focus to discover the root causes of the problem. Over a 4-day period the team observed the process in action, processing 178 parts in total. The automatic enforcement of line stoppages had been switched off, because the monitoring system would otherwise have stopped the line at nearly every part that was processed. The 25-mm drills at workstation 10A did not produce any irregular behavior, but the 9-mm drills at station 14B showed frequent high peaks in torque, which would normally cause the monitoring system to shut down the line. The team inspected the drills involved but found no signs of wear out. Apparently, the signals were not caused by drill wear out but had another cause.

The automated monitoring system produces graphs such as those shown in Figure 2. The graphs display the torque profile over a cycle in the production process (a single part). The figure shows a typical example of the torque profile of drills that the team identified as worst-of-the-worst (WOWs)

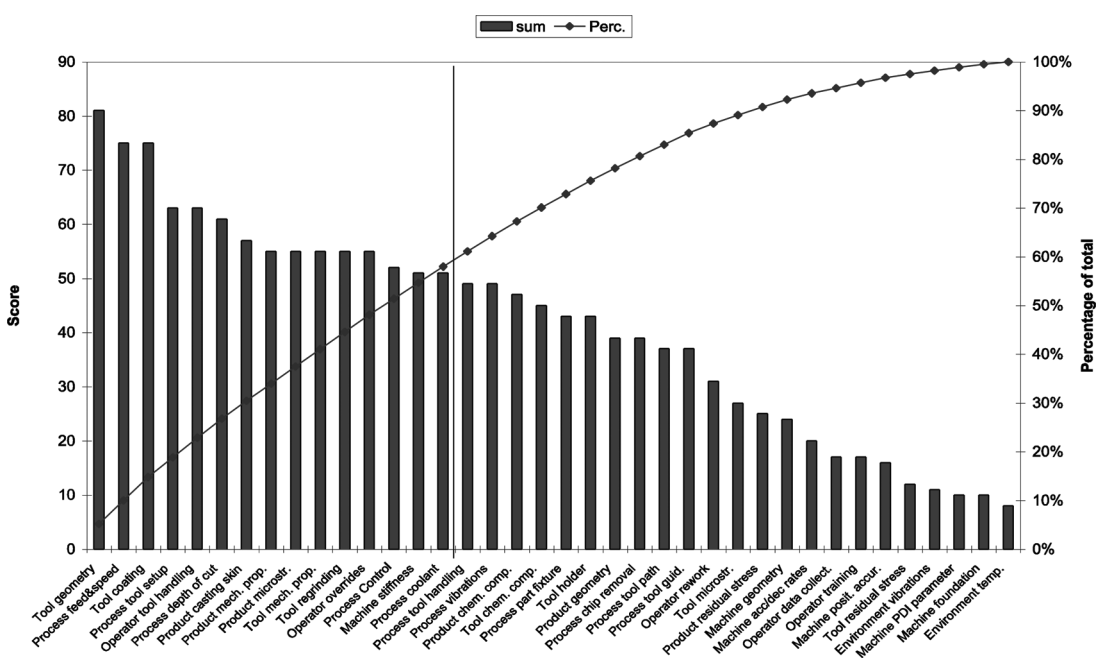

FIGURE 1 **Pareto chart of suggested candidate causes, sorted by multivoting. (Color figure available online.)**

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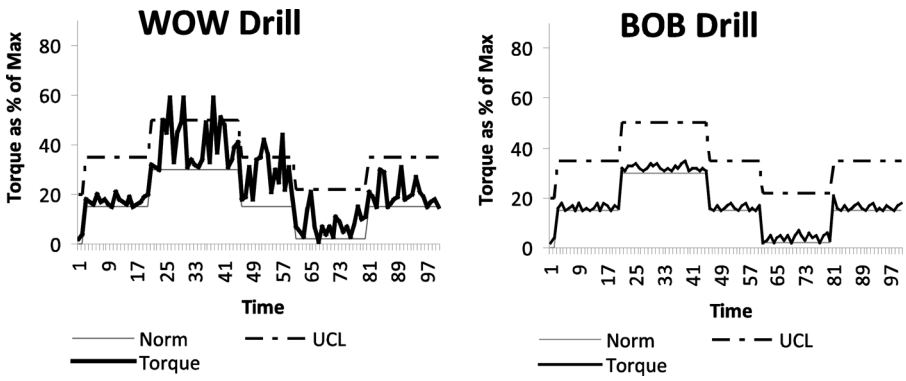

FIGURE 2 **Torque profile over a production cycle for a WOW and a BOB drill.**

and a typical example of a best-of-the-best (BOB) drill. As evident in the graphs, the torque of the WOW drills frequently is beyond the upper control limit (UCL).

The team defined a quality scale for indicating the severity of the problem: 1 for extremely good situations (no peaks in torque visible) and 5 for extremely bad situations (high peaks); 3 is moderate. The team observed that the high peaks in torque occurred mainly in high feed periods. Station 14B features seven drills. The first six are driven by three motors (two drills per motor). The seventh drill has a longer path in the part and is driven by its own motor. This seventh drill suffered more from high torque peaks than the other six and was selected for further study.

The team laid down the physical structure of a drill, decomposing it into its parts. The following components were identified:

- The drive spindle
- The drill
- The bearing, including chip catchers
- The drill bush
- The cast product

To discover in which part of the system the root cause must be, the team did a component search study (cf. Bhote, 1991) by disassembling, assembling, and swapping successively the various components: spindle, drill, bearing, and bush. They selected a drilling position that had a very poor performance (high torque peaks in each of 11 processed parts), designated as WOW, and a drilling position with a good performance (no peaks in 9 processed parts), designated as BOB. The team verified that after taking apart these two drilling positions and then putting them back again, the WOW was still performing poorly and the BOB was still performing well. To establish this, both the WOW and the BOB positions were disassembled and assembled again three times, without interchanging any components; the resulting ratings are plotted in Figure 3 (values of 5, 4, 4 for the WOW position, and three 1s for the BOB position). The dashed lines in the graph are decision limits, comparable to control limits in a control chart, that delimit values to be interpreted as WOW results (values in between the upper two dashed lines) and BOB results (values in between the lower dashed lines). The decision limits are determined from the variation in the first series of two times three disassemblies/assemblies (without swapping components). The decision limits are calculated as in Bhote (1991).

After swapping the spindles, bearings, and bushes, the WOW position was still performing poorly, and the BOB position was performing well. But after swapping the drills, the performance of the WOW and BOB positions completely reversed: the BOB

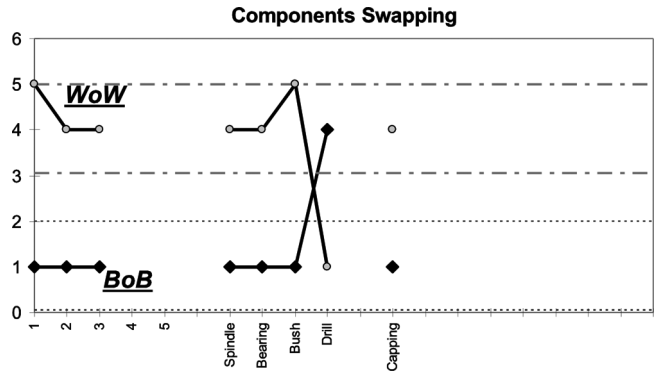

FIGURE 3 **Results of the component search study. The dashed lines are decision limits. (Color figure available online.)**

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position now had results within the decision limits for WOW values and vice versa. Swapping the drills back to their original positions (the capping run in Figure 3) turns the WOW position into WOW performance again and the BOB position into BOB performance.

The team concluded that the problem was caused in the drill, including the drill head, but not in the bearing and chip catchers. Some drills showed peaks in torque regardless of which part was processed with them, whereas other drills had no peaks, irrespective of the parts being processed. Thus, the team had achieved focus and studied properties of the drills in more detail.

FOCUSING ON PROPERTIES OF THE DRILL

The team selected five poorly performing drills (WOWs) and five very good drills (BOBs) and grouped them together in five pairs. All of the drills were checked on a number of characteristics such as dimensions but also on some visual aspects. The idea behind this so-called pairwise comparison technique is to find clues that can lead to the actual cause of the difference between BOB and WOW situations. With pairwise comparison the problem solver looks for characteristics that are consistently different between a BOB and a WOW specimen in each of the investigated pairs. None of the dimensions showed a consistent pattern within all pairs, but one of the visual aspects showed a consistent pattern when comparing each pair (see Figure 4).

A pairwise comparison study can be effective when the search space is not too extensive; that is, when the preceding investigations have narrowed down the search to an orderly and compact area for which it is possible to define a manageable list of characteristics that can be evaluated. Comparing a BOB and a WOW machine makes no sense: the search area would be much too large and the list of characteristics to be evaluated is unbridgeable!

The pattern that emerged in comparing the five WOW and BOB drills included visible grinding artifacts on the cutting edges of the drills that were present for all BOB drills but absent for the WOW drills. These imperfections seemed to improve the performance of the drills, to the extent that their absence appeared to be responsible for the behavior triggering frequent out-of-control signals from the monitoring system. This could be understood because these artifacts could function as chip breakers, resulting in smaller chips that can be removed more easily by the cooling liquid. The team reasoned that the absence of such artifacts on the cutting edges would result in larger chips, which may create obstructions and cause peaks in torque. This conclusion suggested a remedy for the problem: redesigning the drills to include similar artifacts that function as chip breakers.

Frequent line stoppages, triggered by the monitoring system in order to prevent impending drill breaks, turned out to be unrelated to drill wear out and instead were caused by problems in the removal of chips. Obstructions caused by larger chips resulted in out-of-control torque values and ensuing line stoppages. A great help in tracking down this root cause was the coincidental presence of imperfections in the cutting edges of the drills, which turned out to function as chip breakers, thereby providing a remedy for the problem.

DISCUSSION

The case is an illustration of the importance of focus in diagnostic problem solving. The first attempt at discovering the root cause followed the often

		Pair 1		Pair 2		Pair 3		Pair 4		Pair 5	
		BOB_1	WOW_1	BOB_2	WOW_2	BOB_3	WOW_3	BOB_4	WOW_4	BOB_5	WOW_5
	Performance (Spike Level)	*1*	*5*	*1*	*4*	*1*	*5*	*1*	*5*	*1*	*5*
Features to evaluate	Top angle	125	130	110	105	110	115	130	115	125	120
	Side angle	78	80	80	80	75	80	85	75	80	75
	Sagging	0.12	0.10	0.13	0.09	0.11	0.12	0.12	0.09	0.11	0.13
	Dimension A	7	7	8	5	7	8	9	5	6	7
	Dimension B	34	30	33	35	33	32	30	31	30	31
	Width	8	9	7	8	9	8	8	9	8	8
	Diameter at point X	467	360	404	460	432	564	476	454	576	489
	Stains near top	Y	N	N	N	N	Y	N	N	N	N
	Discoloration	mild	no	yes	yes	no	no	no	mild	no	yes
	Cutting edge appearance	Artifact	OK	Artifact	OK	Artifact	OK	Artifact	OK	Artifact	OK

FIGURE 4 **Results of the pairwise comparison study between five BOB and five WOW drills. (Color figure available online.)**

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suggested combination of brainstorming and experimentation, often prescribed in quality problem solving and Six Sigma. The idea is to generate a list of candidate causes—for example, by brainstorming—and, next, use a statistically designed experiment to identify the causes having the largest effect. Such a strategy is not bad in itself but only after sufficient focus has been achieved; that is, after the search space of potential causal explanations has been narrowed down to a relatively compact area.

Such narrowing down, early in the problem-solving process, could be done by so-called branch-and-prune tactics (De Mast 2011). Whereas brainstorming is a divergent process, aimed at widening the range of options, such branch-and-prune tactics are convergent approaches that rule out options. They have the problem solver split the search space into disjoint classes of causes (the branch step) and then use evidence to rule out all but one or two of the classes (prune). Next, these retained classes are studied in more detail, splitting them up in subclasses and aiming for another pruning step. This creates a hierarchical way of working: in the early stages the problem solver studies broad and general causal directions, and pruning eliminates whole categories of causes at once, obviating the need to study them in more detail. Only promising causal directions are elaborated into more specific and detailed causes.

The team in the example did a number of branch-and-prune steps. By observing where the problem was and where it was not, drill position number 7 at workstation 14B came into focus, and all other parts of the process could be discarded from further investigation. The next branching and pruning steps were done on the basis of the physical structure of the system: by swapping components and observing which combinations resulted in torque peaks, the team could rule out all components except the drills themselves. At this stage the search space had been narrowed down substantially, and visual comparisons brought to light the root cause of the problem, obviating a multifactor experiment to identify the cause.

Branch-and-prune tactics are typically not prescribed in accounts of Six Sigma's define–measure–analyze–improve–control (DMAIC) method (compare, for example, George et al. [2004], pp. 12–13; Gitlow and Levine [2005], pp. 146ff., who favor the above-mentioned combination of brainstorming and designed experiments). They are, on the other hand, the backbone of Shainin's methodology for problem solving (Steiner et al. 2008). Shainin prescribes techniques such as the multivari study, component search, and pairwise comparisons for achieving focus. Once the search space has been narrowed down, variables search or a factorial experiment pinpoint the factor having the largest effect. In addition, Kepner and Tregoe's (1997) problem analysis method is based on branch-and-prune thinking, as demonstrated in De Mast (2011).

In the example, the team initially did not start with a branch-and-prune strategy but, instead, immediately started with a brainstorming session. This created a long list of candidate causes—too many (and maybe also too vague and general) for experimentation to identify the right ones. The case illustrates one of the dangers of the brainstorming/experimentation approach without first establishing sufficient focus. The first danger is that the search space is so extensive that potential causes are not enumerable or otherwise multitudinous, and testing all of them, even with an efficient experimental design, is too laborious. The second danger is that the problem solver, faced with an extensive search space, only raises candidate causes in a narrow area of the space and thus may get bogged down in the wrong part of the search space. In particular, problem solvers may be tempted to fixate on the usual suspects. The third danger is that the problem solver raises candidate causes that are too general and nonspecific to really allow useful experimentation. A last danger is in interpreting the results of an experiment. Factors that turn up as having large effects in the experiment are not necessarily the causes of the problem under study, because the effects of factors in an experiment are partly determined by the chosen high and low settings. If the chosen high and low settings are not representative of the levels that factors attain in the process, the effects of the factors on the problem under study may be overestimated.

The hierarchical way of working branch-and-prune tactics ensures efficiency of the diagnostic search by preventing excessive divergence of the search. Their scant coverage in many accounts of Six Sigma is a surprise.

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