

How to perform process capability studies

John H. Rutherford

ABSTRACT: *Many factors are involved in a production process. In the absence of outside influences, the process produces a predictable series of events that are collectively referred to as process capability. To determine process capability, a capability index, which compares the natural tolerance of the process to specification limits, is calculated. A process capability study is done to determine whether a process is capable of performing within specifications. If a process is found to be incapable, corrective actions are taken. In addition to the process capability study, this paper presents information on the machine capability study.*

KEYWORDS: *Capacity, corrugated boxes, paper making equipment, personnel, procedures, processes, productivity, raw materials, specifications, statistical methods, statistical process control, test equipment, work study.*

Many elements are involved in the process of producing corrugated boxes—raw materials, manufacturing and testing equipment, manufacturing procedures, and personnel. The term *process* refers to any set of conditions or causes that work together to produce a given result. Within a process, there are many factors that work together to achieve the end result—in this case, the production of corrugated boxes. When allowed to operate without interference from outside influences, the process produces a predictable series of effects that

leads to a product that consistently performs within a given range. This series of effects, which can also be described as the normal behavior of the process when in statistical control, is known as *process capability* (1).

This paper covers the generation of a process's capability index, which is necessary to (a) determine the ability of the process to stay within desired specification limits, (b) demonstrate the steps recommended to conduct a process capability study, and (c) discuss the benefits of the machine capability study.

Determining process capability statistically

In order to determine process capability, the range of tolerance is compared to the process's statistical limitations. The *range of tolerance* is the range between the upper and lower specification limits. These limits are usually agreed upon between the customer and vendor. The statistical limitations, on the other hand, are defined by the process and are set at ± 3 standard deviations ($\pm 3\sigma$); this includes 99.7% of all process output and is the basis for control chart work. The *statistical limitation* of a process is defined as six sigma (6σ) and may also be called the *natural tolerance* of the process (2).

A process's *capability index* is a comparison of its natural tolerance to the specification limits. The capability index, C_p , can be calculated with the following formula:

$$C_p = (USL - LSL)/6\sigma \quad (1)$$

where

C_p = Capability index

USL = Upper specification limit

LSL = Lower specification limit

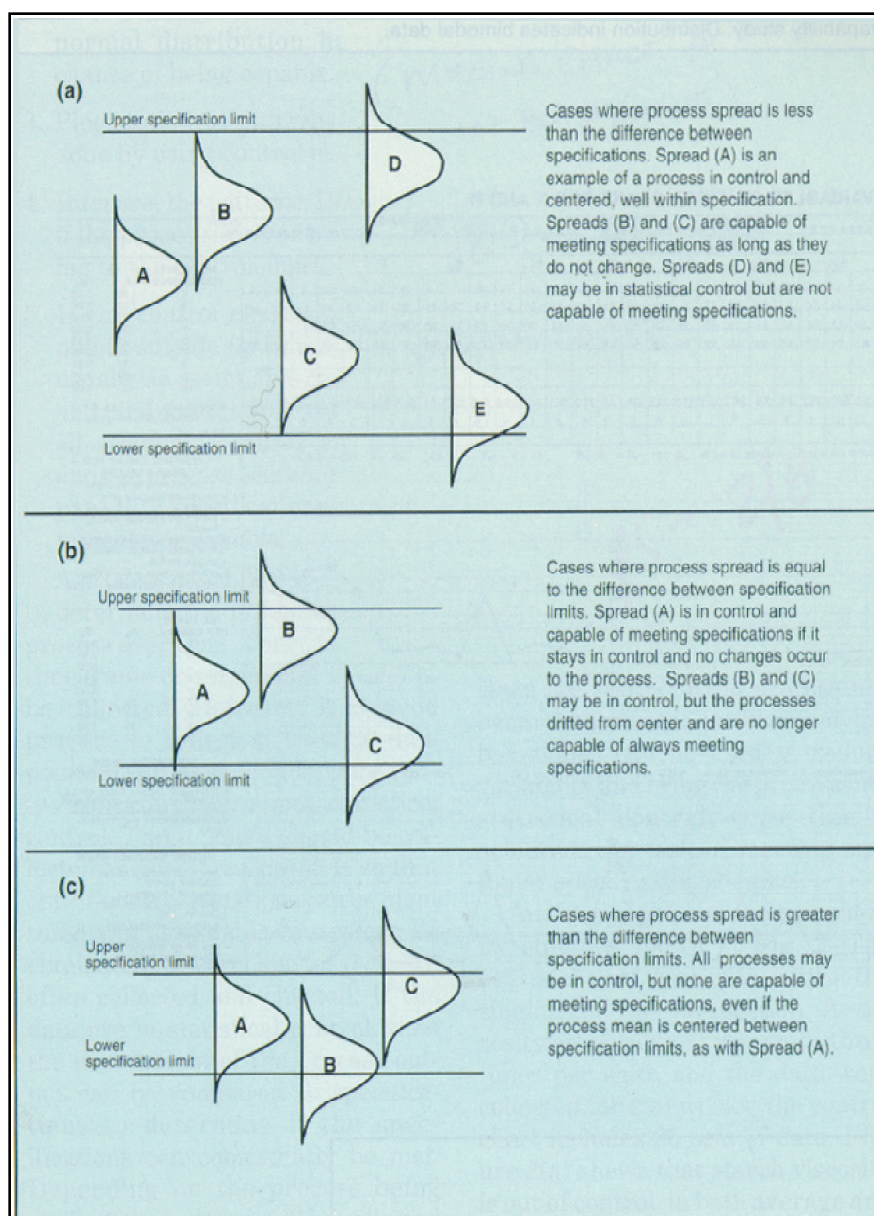
6σ = Natural tolerance.

When the capability index is equal to or greater than 1.0, the process is capable of operating within the process tolerance (6σ), or within specifications. If the value is less than 1.0, the process is not capable of operating within 6σ .

Unfortunately, the capability index does not accurately indicate process shifts, or the "centering" of the process. As a result, C_{pk} is often

Rutherford is a senior process engineer at Inland Container Corp., 4030 Vincennes Rd., Indianapolis, IN 46268-0937.

1. Examples of process spreads (range of tolerance) as they compare to specification limits



ducer and user, most statisticians define a Cpk equal to or greater than 1.33 as being capable. A Cpk of 1.33 is equivalent to a centered process with a capability of $\pm 4\sigma$ (3). The higher minimum value of Cpk (1.33, as opposed to 1.0 for Cp) permits process shifts within the specification limits without causing the process to produce out-of-specification product.

The following statements apply to the capability index, Cpk:

- Cpk indicates whether the process can operate within specification limits.
- If Cpk is equal to Cp, the process is centered between the specification limits.
- If Cpk is between 0 and 1.0, some of the 6σ spread falls outside the specification limits.
- If Cpk is between 1.0 and 1.33, the 6σ spread is completely within specification limits but does not allow a safe margin of error for process shifts.
- If Cpk is negative, even the process mean is outside the specification limits (2).

For example, a Cpk of 0.70 means that 70% of a 3σ spread falls between the process average and the nearest specification limit. The other 30% is outside the specification limits. **Figure 1** (4) demonstrates how the spread of a process may compare to specification limits.

Process capability study

A process capability study is done to determine whether a process is capable of performing within specification. The study generally follows a five-step approach (1):

1. Collect data from the process.
2. Determine if the data describe a "normal" process. This is best done by arranging the data into a histogram. If the distribution is

used to predict process capability. Cpk is determined by calculating two indices—an index for comparing the upper specification limit with the upper process limit and an index for comparing the lower specification limit with the lower process limit. The formulae used for the determination are as follows:

$$C_{pu} = (USL - \bar{X})/3\sigma \quad (2)$$

and

$$C_{pl} = (\bar{X} - LSL)/3\sigma \quad (3)$$

where

C_{pu} = Upper half capability index

C_{pl} = Lower half capability index

USL = Upper specification limit

LSL = Lower specification limit

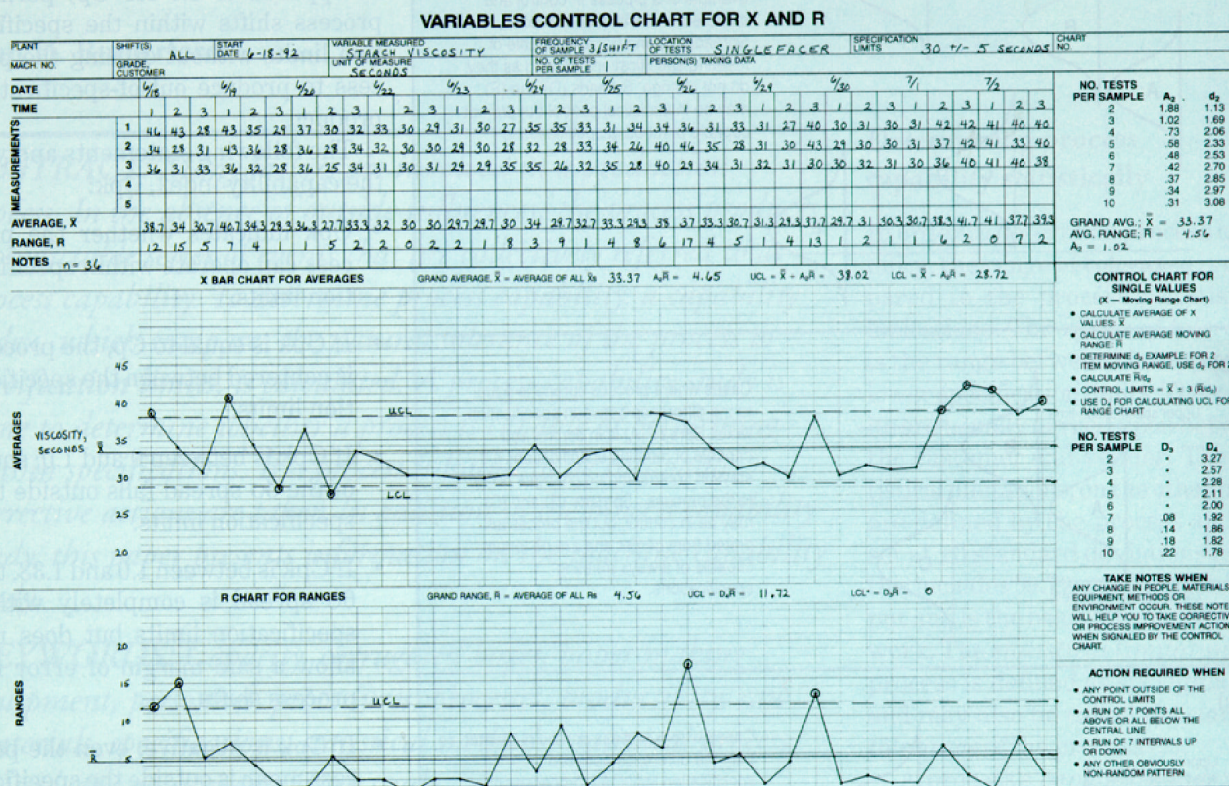
$\bar{X}$ = Process average

3σ = 3 standard deviations.

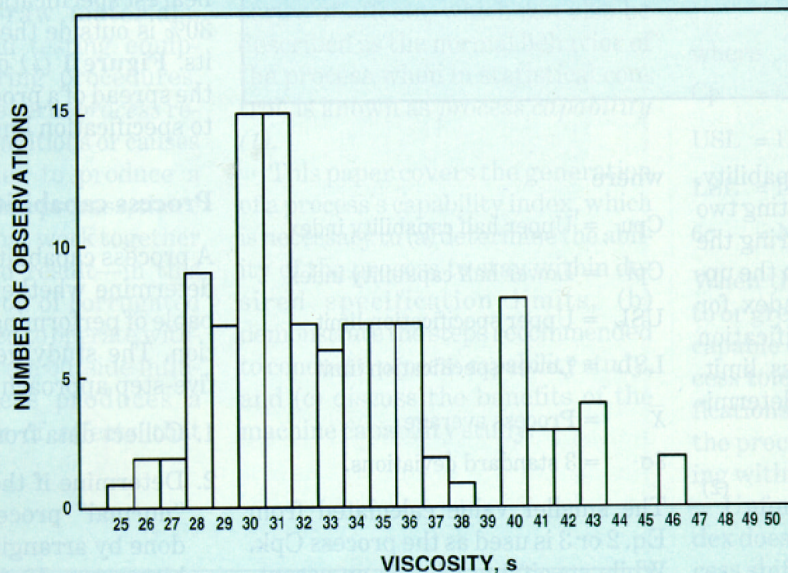
The smaller value calculated from Eq. 2 or 3 is used as the process Cpk. While specifying what is an acceptable Cpk is negotiable between pro-

2. Process capability study of starch viscosity at the singlefacer. Original study included gathering 36 sets of data over a two-week period. (a) Original data show process is out of control. Eight averages and four ranges are outside of control limits. (b) Frequency distribution of individual viscosity tests taken during process capability study. Distribution indicates bimodal data.

A



B



normal, proceed to Step 3. If it is not, determine the cause. A non-normal distribution has little chance of being capable.

3. Plot statistical patterns. This is done by using control charts.
4. Interpret the patterns. Determine if the process is in control according to the control chart.
5. If the control chart shows data points outside 6σ limits, there is usually an assignable cause. Find and eliminate these causes. Once all assignable causes are found and the process is in control, compare it to specifications to determine if it is capable.

A process capability study is used to determine the predictability of a process over time. There is no given time frame or set amount of data to be collected. However, it is good practice to collect at least 20 data points to prepare an adequate control chart for determining statistical control. These points should be collected as quickly as possible so that out-of-control situations can be identified and assignable causes can be eliminated. Several sets of data are often collected and charted. If the data are in statistical control, then the distribution of the process output can be compared to specifications to determine if the specifications can consistently be met. Depending on the process being studied, these data could be collected in a few days (such as with the board edge crush test or board caliper), a period of weeks (e.g., when measuring starch viscosity), or perhaps longer (such as when collecting steam pressure or corrugator roll wear data). It is important to allow enough time so that any special (assignable) cause that affects the process capability can be identified.

The outcome of a process capability study may describe one of the following scenarios:

- The process is in control statistically but is not capable of meeting customer specifications. This can occur when specification limits are too restrictive or the process is operating at an average too near one of the specification limits.
- The process is out of statistical control but still capable of meeting customer specifications. This can happen if specification limits are too wide and if the process average is near the center of the specification range. Any shift of the process or other loss of control can easily push it outside the specification limits.
- The process is out of statistical control and is not capable of meeting customer specifications.

Once the status of the process has been determined, problem-solving techniques can be used to reduce variability and bring the process into statistical control. Once this is achieved, the task of meeting customer specifications begins.

An example of a process capability study is shown in **Fig. 2**. The consistency of starch viscosity at the singlefacer was in question. A viscosity measurement was made three times per shift, and the data were collected for two weeks; the control chart includes 36 sets of data. Figure 2(a) shows that starch viscosity is out of control, in both average and range. Over the course of the study, eight viscosity points fell outside the control limits, and four range points were out of control. A histogram of the individual viscosity checks [Fig. 2(b)] taken during the study clearly indicates that the distribution is not normal; it is skewed to the left and somewhat bimodal (two data peaks: one at 30–31 seconds and another at 40 seconds).

If plant personnel kept track of the assignable causes that led to the out-of-control points, each of those points could be removed from the charts, and new control limits could

be calculated. If the remaining data appear normal and the new chart is in control, then process capability can be determined. If the process is still out of control, and assignable causes can be found for out-of-control data, that data can be removed and a new chart prepared. Assuming that this was done for the viscosity data, a new histogram indicates that the remaining data distribution is approaching normal. The process is now in control [**Fig. 3(a)**], the new histogram is shown in **Fig. 3(b)**, and process capability can finally be calculated. From the remaining data, the standard deviation can be estimated with the following formula:

$$\bar{R}/d_2 = \text{Standard deviation} \quad (4)$$

where

$\bar{R}$ = Average range

d_2 = Statistical constant.

and C_p and C_{pk} can be calculated. In this case, 17 data points remained after all causes were resolved. The capability index, C_p , was 1.26, an indication that the process is capable of meeting specifications. However, a C_{pk} of 0.99 indicated that some values are falling outside the specification limits of 30 ± 5 seconds. Therefore, the process is not capable of meeting these specifications 100% of the time.

It is not likely that all assignable causes can be identified on a chart with many out-of-control points. Additionally, even if all assignable causes are found, preferably 75–80% of the original data should remain for a valid study. A more likely scenario is shown in **Fig. 4(a)**. After addressing all assignable causes that could be found, more data were collected and a new control chart constructed. This time all 36 data points fell within the control limits. The histogram, **Fig. 4(b)**, shows a normal distribution of the data. With the process in control and normal, the process capability study can be completed by calculating C_p and C_{pk} . This time $C_p = 1.23$, still indicating

3. Process capability study of starch viscosity at the singlefacer. (a) This scenario assumes that all assignable causes were found and the out-of-control points could be resolved. (b) Frequency distribution of individual viscosity tests remaining in process capability study, assuming assignable causes could be identified to allow removal of some test results from the distribution. The shape of the data approaches a normal bell curve distribution.

A

Capability indices:

$$C_p = \frac{USL - LSL}{6(\hat{\sigma}/d_2)} = \frac{35 - 25}{6(2.24/1.69)} = \frac{10}{7.95} = 1.26$$

$$C_{pk} = \text{the lower of } C_{pu} \text{ or } C_{pl} = 0.99$$

$$C_{pu} = \frac{USL - \bar{X}}{3(1.325)} = \frac{35 - 31.04}{3.98} = 0.99$$

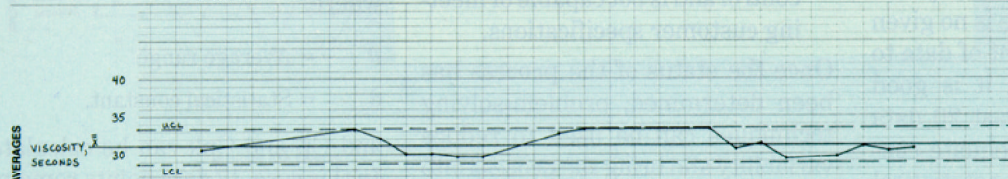
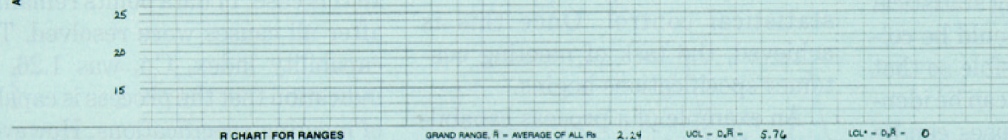
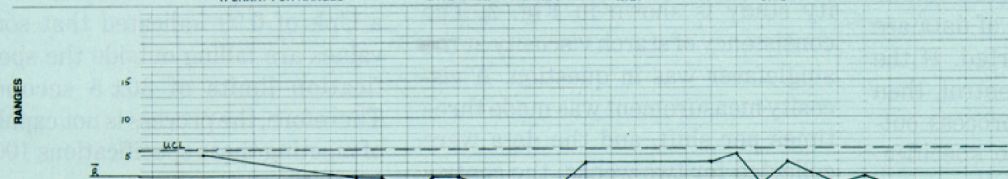
$$C_{pl} = \frac{\bar{X} - LSL}{3(1.325)} = \frac{31.04 - 25}{3.98} = 1.52$$

$C_{pk} < 1.33$; therefore, the process is not capable

VARIABLES CONTROL CHART FOR X AND R

PLANT	SHIFT(S)	START DATE	VARIABLE MEASURED	FREQUENCY OF SAMPLE	LOCATION OF TESTS	SPECIFICATION LIMITS	COUNT NO.																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
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X BAR CHART FOR AVERAGES GRAND AVERAGE $\bar{\bar{X}} = \text{AVERAGE OF ALL } \bar{X}_i = 31.04$ $A_{29} = 2.28$ $UCL = \bar{\bar{X}} + A_2\bar{R} = 33.32$ $LCL = \bar{\bar{X}} - A_2\bar{R} = 28.76$



NO. TESTS PER SAMPLE	A_2	d_2
2	1.88	1.13
3	1.02	1.69
4	.73	2.06
5	.58	2.33
6	.48	2.53
7	.42	2.70
8	.37	2.85
9	.34	2.97
10	.31	3.08

GRAND AVG.: $\bar{\bar{X}} = 31.04$
AVG. RANGE: $\bar{R} = 2.24$
 $A_2 = 1.02$

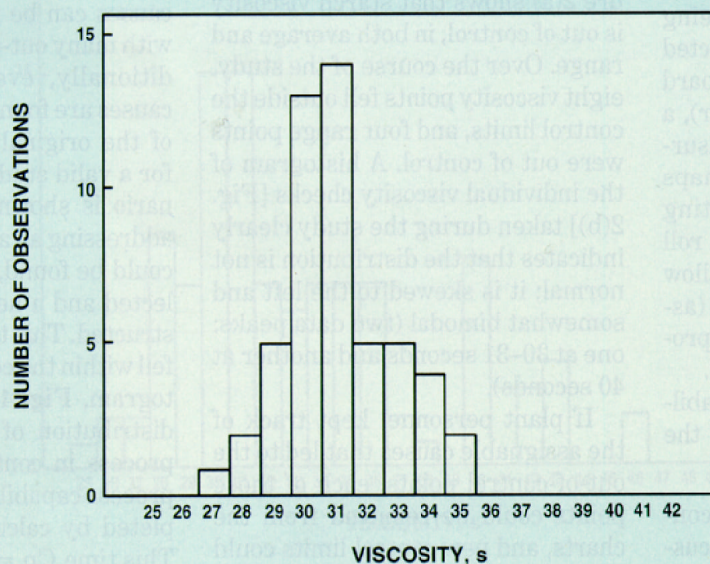
CONTROL CHART FOR SINGLE VALUES
($\bar{X}$ - Moving Range Chart)
• CALCULATE AVERAGE OF $\bar{X}$ VALUES, $\bar{\bar{X}}$
• CALCULATE AVERAGE MOVING RANGE, $\bar{R}$
• DETERMINE d_2 EXAMPLE: FOR 2 ITEM MOVING RANGE, USE d_2 FOR 2
• CALCULATE R_{10}
• CONTROL LIMITS - $\bar{\bar{X}} \pm 3(\bar{R}/d_2)$
• USE D_4 FOR CALCULATING UCL FOR RANGE CHART

NO. TESTS PER SAMPLE	D_3	D_4
2	*	3.27
3	*	2.57
4	*	2.28
5	*	2.11
6	*	2.00
7	.08	1.92
8	.14	1.86
9	.18	1.82
10	.22	1.78

TAKE NOTES WHEN
ANY CHANGE IN PEOPLE, MATERIALS, EQUIPMENT METHODS OR ENVIRONMENT OCCUR. THESE NOTES WILL HELP YOU TO TAKE CORRECTIVE OR PROCESS IMPROVEMENT ACTION WHEN SIGNALLED BY THE CONTROL CHART.

ACTION REQUIRED WHEN
• ANY POINT OUTSIDE OF THE CONTROL LIMITS
• A RUN OF 7 POINTS ALL ABOVE OR ALL BELOW THE CENTRAL LINE
• A RUN OF 7 INTERVALS UP OR DOWN
• ANY OTHER OBVIOUSLY NON-RANDOM PATTERN

B



4. New process capability study of starch viscosity at the singlefacer. (a) This scenario assumes that, after resolving as many data points as possible, the process was still out of control. Therefore, more data were collected and replotted. Since the assignable causes that were found were controlled, this time the data were in statistical control. Capability can be determined. (b) Frequency distribution of individual viscosity tests a from repeated process capability study. Assignable causes were addressed, and a new study was done. The data form a normal bell curve distribution.

A

Capability indices:

$$C_p = \frac{35-25}{6(R/d_2)} = \frac{10}{6(2.28/1.69)} = \frac{10}{8.1} = 1.23$$

$$C_{pl} = \frac{30.83-25}{3(1.35)} = 1.43$$

$$C_{pu} = \frac{35-30.83}{3(1.35)} = 1.04$$

$$C_{pk} = C_{pu} = 1.04$$

Since $C_{pk} < 1.33$, the process is not capable

VARIABLES CONTROL CHART FOR $\bar{X}$ AND R

PLANT	SHIFT(S)	START DATE	VARIABLE MEASURED	FREQUENCY OF SAMPLES	LOCATION OF TESTS	SPECIFICATION LIMITS	CHART NO.
	ALL	7-6-92	STARCH VISCOSITY	3/SAMPLE	SINGLEFACER	30 +/- 5 SECONDS	
MADE NO.	GRADE		UNIT OF MEASURE	NO. OF TESTS PER SAMPLE	PERSON(S) TAKING DATA		
	CUSTOMER		SECONDS				
DATE	TIME	7/6	7/7	7/8	7/9	7/10	7/11
		7/12	7/13	7/14	7/15	7/16	7/17
		7/18	7/19	7/20	7/21	7/22	7/23
		7/24	7/25	7/26	7/27	7/28	7/29
		7/30	7/31	7/32	7/33	7/34	7/35
		7/36	7/37	7/38	7/39	7/40	7/41
		7/42	7/43	7/44	7/45	7/46	7/47
		7/48	7/49	7/50	7/51	7/52	7/53
		7/54	7/55	7/56	7/57	7/58	7/59
		7/60	7/61	7/62	7/63	7/64	7/65
		7/66	7/67	7/68	7/69	7/70	7/71
		7/72	7/73	7/74	7/75	7/76	7/77
		7/78	7/79	7/80	7/81	7/82	7/83
		7/84	7/85	7/86	7/87	7/88	7/89
		7/90	7/91	7/92	7/93	7/94	7/95
		7/96	7/97	7/98	7/99	7/100	7/101
		7/102	7/103	7/104	7/105	7/106	7/107
		7/108	7/109	7/110	7/111	7/112	7/113
		7/114	7/115	7/116	7/117	7/118	7/119
		7/120	7/121	7/122	7/123	7/124	7/125
		7/126	7/127	7/128	7/129	7/130	7/131
		7/132	7/133	7/134	7/135	7/136	7/137
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		7/678	7/679	7/680	7/681	7/682	7/683
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		7/738	7/739	7/740	7/741	7/742	7/743
		7/744	7/745	7/746	7/747	7/748	7/749
		7/750	7/751	7/752	7/753	7/754	7/755
		7/756	7/757	7/758	7/759	7/760	7/761
		7/762	7/763	7/764	7/765	7/766	7/767
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		7/852	7/853	7/854	7/855	7/856	7/857
		7/858	7/859	7/860	7/861	7/862	7/863
		7/864	7/865	7/866	7/867	7/868	7/869
		7/870	7/871	7/872	7/873	7/874	7/875
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		7/984	7/985	7/986	7/987	7/988	7/989
		7/990	7/991	7/992	7/993	7/994	7/995
		7/996	7/997	7/998	7/999	7/1000	7/1001
		7/1002	7/1003	7/1004	7/1005	7/1006	7/1007
		7/1008	7/1009	7/1010	7/1011	7/1012	7/1013
		7/1014	7/1015	7/1016	7/1017	7/1018	7/1019
		7/1020	7/1021	7/1022			

a process capable of meeting specifications. Cpk is 1.04, indicating a process that meets specifications but leaves little room for process shifts. The Cpu is 1.04 while the Cpl is 1.43, indicating that the process is shifted to the high side of the specification limits. Because Cpk is less than 1.33, the process is not capable.

Corrective actions

When a process is incapable of meeting specifications, there are three steps that can be taken to resolve the problem (5): (a) accept the situation and sort, rework, and/or scrap the product that falls outside specifications, (b) change the specifications, or (c) change the process.

Most plants have at some time followed Step (a). This is usually not acceptable because it costs the plant time and money. Step (b) may be used if the plant and its customer determine that the as-received product is acceptable, and changing the specifications to match process performance is not going to adversely affect the finished product. However, changing specifications to match the natural process tolerance is risky and must have the agreement of all involved parties—even if the “customer” is the corrugator crew and the “vendor” is the starch system.

The first consideration should be to change the process. This is best accomplished by eliminating assignable causes of variation and changing procedures to better center the process within the specification limits. This should be done in consideration of cost problems that may arise. If bringing the process into full capability involves excessive cost (capital expense, lost production, etc.), the specifications should be reviewed. Remember that the natural tolerance of the process should not

exceed 75% of the specification ($Cpk = 1.33$) and that natural process drift occasionally leads to defectives. As previously mentioned, specifications that are as wide as the product (and customer) can accept help minimize manufacturing costs (2).

Machine capability study

One variation of the process capability study that should also be considered is the machine capability study. This study, done on a particular machine such as a flexo rather than studying the entire process, can be done rapidly and provides a snapshot of the machine's potential capability.

The basic premise of a machine capability study is to measure capability with all sources of variation removed or controlled. In order to do a study, the process on a given machine is chosen and the following conditions should be met:

- All current machine conditions should be noted.
- One operator should perform this and all future studies.
- All samples must come from the same raw materials. If studying the corrugator, board should be made from one set of roll stock. At the flexo, boxes should all come from one order.
- The same gauge(s)/testing device(s) must be used throughout the study.
- Do not assume the measuring device for the test is accurate. Check its calibration (this goes back to controlling variation).
- Collect data, at least 20 points at a time, and plot to determine statistical control.

- Once control is established, collect and measure 100 consecutive samples.
- Calculate machine capability in the same manner as previously described.

Machine capability is particularly useful in studying finishing equipment's ability to produce consistent slot depth, slot width, print crush, etc. It can also be used at the corrugator cutoff knife, for caliper off the corrugator, and for pin adhesion. It is a relatively quick study and can be conducted on new equipment, after a machine rebuild, after a major part change (like a feed roll), or as a troubleshooting tool.

Process capability studies are useful tools for any area in the boxplant. They can help plant personnel find causes of variation in their processes; by controlling these sources of variation, they can improve the plant's productivity and reduce many forms of waste. The techniques presented give any plant the rudiments for performing its own process capability studies. ▀

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