

What is Process Capability Analysis (PCA)?

Hint ... it helps you measure how AMAZING your AMAZING process is...



WORKBOOK

Presented by

Dr Chris Jackson

Reliability engineer



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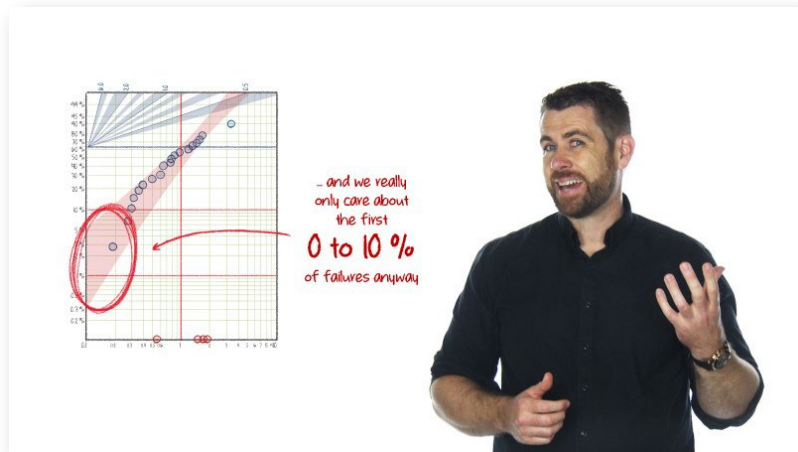
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Who is your teacher? ... Dr Chris Jackson

Dr Jackson holds a Ph.D. and MSc in Reliability Engineering from the University of Maryland's Center of Risk and Reliability. He also holds a BE in Mechanical Engineering, a Masters of Military Science from the Australian National University (ANU) and has substantial experience in the field of leadership, management, risk, reliability and maintainability. He is a Certified Reliability Engineer (CRE) through the American Society of Quality (ASQ) and a Chartered Professional Engineer (CPEng) through Engineers Australia.

Dr Jackson is the cofounder of IS4 online learning, was the inaugural director of the University of California, Los Angeles (UCLA's) Center of Reliability and Resilience Engineering and the founder of its Center for the Safety and Reliability of Autonomous Systems (SARAS). He has had an extensive career as a Senior Reliability Engineer in the Australian Defence Force, and is the Director of Acuitas Reliability Pty Ltd.



He has supported many complex and material systems develop their reliability performance and assisted in providing reliability management frameworks that support business outcomes (that is, make more money). He has been a reliability management consultant to many companies across industries ranging from medical devices to small satellites. He has also led initiatives in complementary fields such as systems engineering and performance-based management frameworks (PBMFs). He is the author of two reliability engineering books, co-author of another, and has authored several journal articles and conference papers.

What is a PROCESS?

There are many ideas of what a **process** is (or is not). The more formal definition of a **process** is ...

... a set of interrelated work activities that transform inputs into outputs.

We are surrounded by **processes**. We are part of **processes**. We use things that are the results of **processes**. Smart technology increasingly means that **processes** are running night and day to help us 'do better' both personally and professionally.

Processes generate 'something.' And that 'something' can be valuable, useful, enjoyable or otherwise worthwhile. But not all **processes** are the same.

Some **processes** are inefficient. Some involve lots of waste and require constant 'reworking' of things already done. Some **processes** don't interact well with human beings (customers and operators).

But perhaps the most important thing we need to remember about **processes** is that ...

... PROCESSES change, evolve, age and deteriorate.

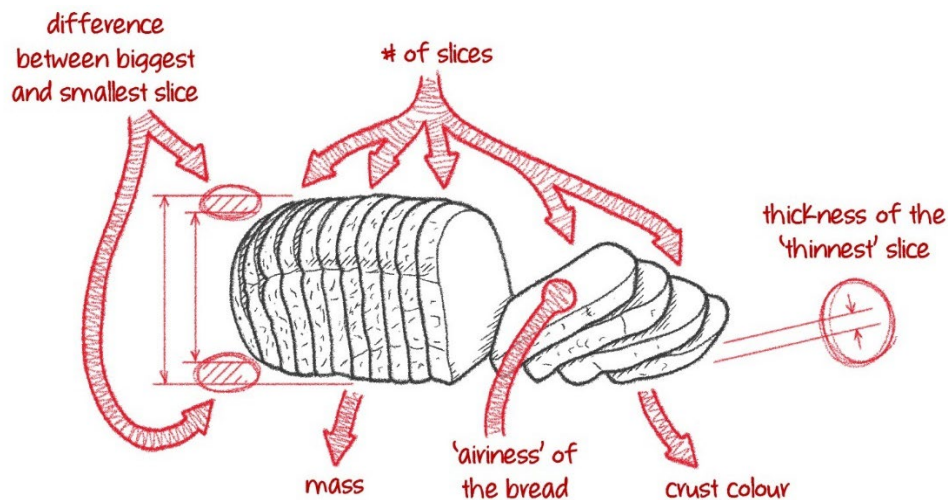
So what can we do to protect ourselves from **processes** that stop doing what we want them to do? This is a very light introduction into how we can '**control**' **processes** so that they stay well within the bounds of what we call 'acceptable.' And the driving principle behind this is PROACTIVITY. That means we leverage activities like **System, Design and Process Failure Mode and Effects Analyses (FMEAs)** to help us identify the likely VITAL FEW issues that are going to negatively affect our process ... along with **corrective actions** to make sure they never happen. But once our **process** is up and running, the fact that it WILL change, evolve, age and deteriorate means we need to continually fight to retain **control**.

And it is much easier to '**stay in control**' than to '**get back in control.**' Whether your **process** starts producing defective products, takes too long, reaches the wrong customer or anything else that represents something 'bad,' there is usually something that could have been done earlier (at very little cost) to make sure we never got here.

the best thing since SLICED BREAD

This guidebook will use the commercial production of sliced bread as an example **process** to study and learn from. Bread is something that most of us enjoy eating daily. And even if you don't ... you can surely relate to similar foods that are produced in similar ways.

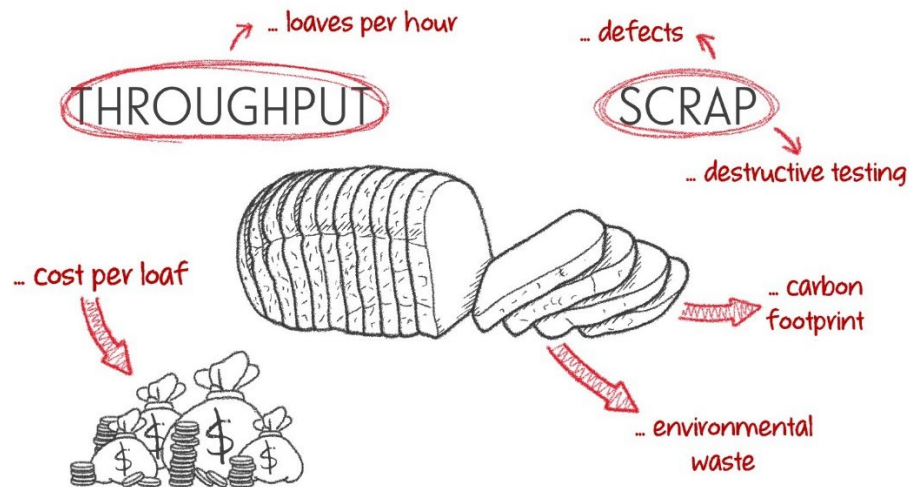
As is the case for most things in life, the **quality** of slice bread can be measured in many ways. A small selection of 'sliced bread characteristics' are illustrated below.



Different characteristics mean different things to different customers. For example, a parent who mainly uses bread to make sandwiches for their children to eat at school might value the consistent size and shape of each slice. They might value bread that has minimal variation between the geometry of the largest and smallest slices in each loaf. Minimal variation makes it much easier to make sandwiches (which usually require two pieces of bread either side of a filling).

And of course ... other customers may value other characteristics of bread more so than geometry. So it is always important to know who your customer or user is, what it is that motivates them, what it is that they value, and (finally) what characteristics of your **process outputs** they consider '**high quality.**'

And while the customer or user is perhaps the most important perspective when it comes to **quality**, we want to make sure our **process** has certain characteristics as well. And some of those considerations for commercial bread making include ...

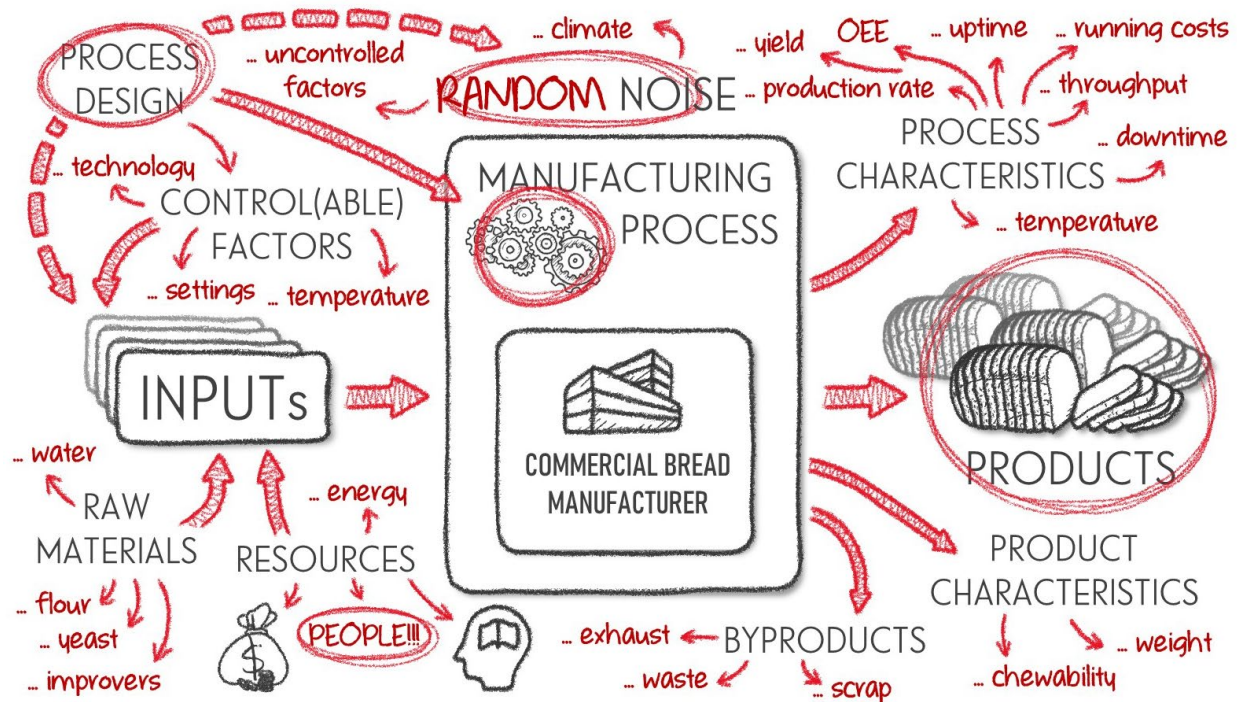


bread doesn't **GENERATE VALUE** ...
... the **PROCESS** that makes bread **GENERATEs VALUE**

We tend to think of **process** 'idealistically.' And that means we often tend to assume that if we provide some **inputs** for our **process** one day, and then provide the same **inputs** the next, we should get the same **output**. That works for arithmetic and algebra where $2 + 2$ will always equal 4. But in the real world, which is not simply analytical and theoretical, we rarely get the same **output** for seemingly identical **process** scenarios. This is because we are surrounded by **random processes**. And random processes frustratingly mean that it is possible to get one of any number of **outputs** for the same **inputs**.



Virtually every practical **process** (manufacturing, software, energy generation, customer management and so on) is essentially **random** in nature. Including commercial bread making.



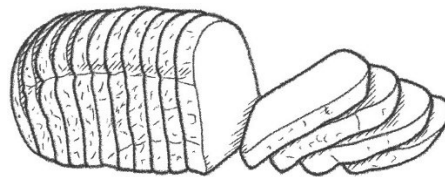
On the left-hand side of the diagram above are **inputs**. There are lots of (slightly and not so slightly different) interpretations of 'common definitions' when it comes to **process design** – particularly manufacturing. **Inputs** generally cover 'everything' that is provided to a **process** – but some people tend to look at **inputs** strictly as **controllable factors**. **Controllable factors** are (for example) the temperature you set the oven in which you bake the bread, the speed at which your conveyor carries ball bearings and so on. Manufacturing often involves raw materials and other resources that include money, people and knowledge such as Intellectual Property (IP). And of course, there are the biggest set of '**controllable factors**' of all ... is the way you design your **process**. This design is obviously very important in terms of things we can control. But it is also very important for the things we cannot (easily) control. And this includes (**random**) **noise** that might be fluctuations in manufacturing plant temperatures, or different training levels of machine operators. A well-designed **process** can minimize the effect that (**random**) **noise** has on our **process**.

On the right-hand side of the commercial bread making **process** diagram on the previous page are the **outputs**. The most important **output** is the **product** (sliced bread). The **product** has a number of characteristics that include things like '**chewability**,' weight, colour, number of slices and so on. These are the characteristics that our customers will use to assess the '**quality**' of our bread. But there are also **process** characteristics that are somewhat independent of the **product**. These include things like uptime, running costs, production rates, throughput, downtime, Overall Equipment Effectiveness (OEE) and so on. It is possible for two identical **products** (in terms of **product characteristics**) to emerge from very different **processes** (in terms of **process characteristics**). Organizations that tend to do well are those that know how to optimize **process characteristics** as part of their own strategy (such as maximizing profit).

But there are also other things that our **process** creates. We call these **by-products** and include things like exhaust (such as CO₂ emissions), waste and scrap. **By-product characteristics** tend to be considered **process characteristics** (such as amount of exhaust create per operating hour). But it is important to remember that **by-products** themselves are not just numbers, and we often need to do something with them.

Keeping an AMAZING PROCESS AMAZING

It often seems difficult to measure what can be subjective things in an objective way. For example ...

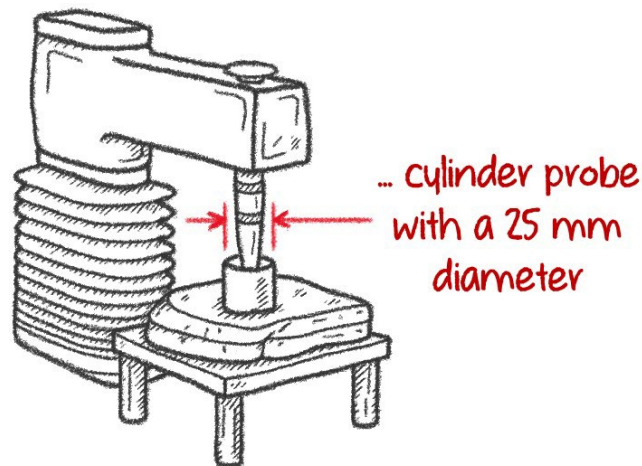


chewability

This might sound like an 'abstract' or 'impractically subjective' metric. But that doesn't mean that we can't attempt to test the 'chewability' of our bread in an objective way.

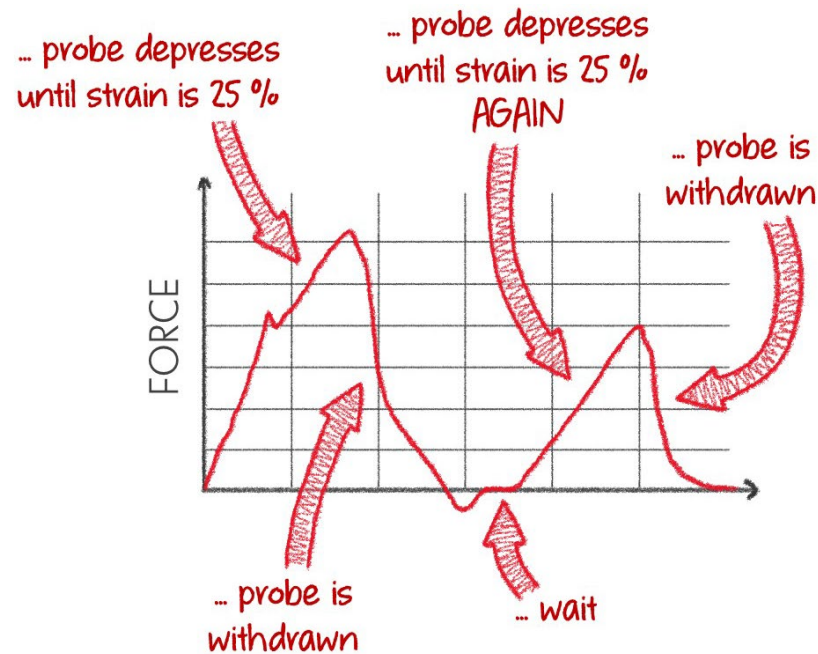
We NEED to measure what we NEED to measure. Not what is EASY to measure.

The challenge for a commercial bread manufacturer is that they need to somehow track the 'chewability' of their bread. It is something that they know drives customer loyalty. And they use a texture analyzer (illustrated below) to do it.

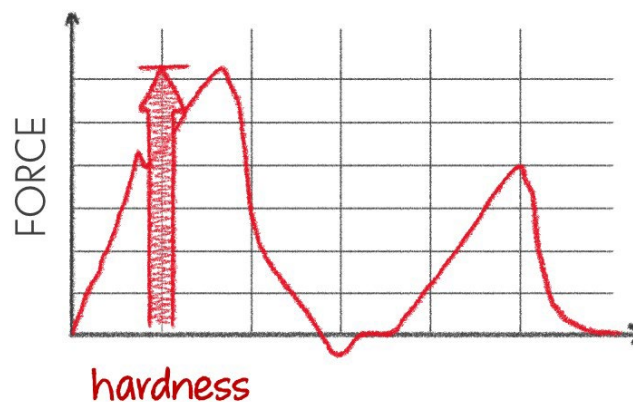


The texture analyzer has the ability to very slowly move an attached probe up and down and measure the smallest of forces that the probe experiences. In the illustration above, two slices of bread are being tested together.

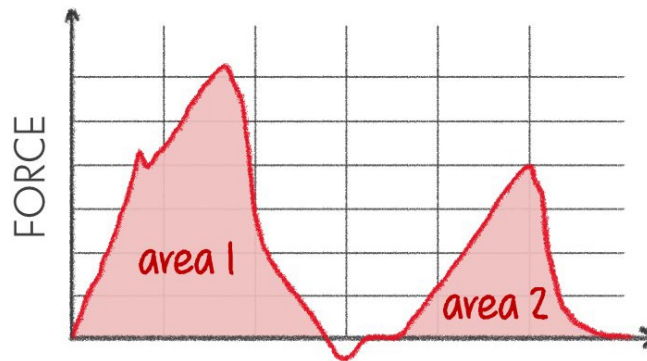
The 'standard' test for bread **chewability** involves the probe being moved down into the bread and out again ... twice. This creates force profile like the one illustrated below.



Three key metrics can be calculated from this profile. The first is **hardness**, which is the maximum force the bread exerts on the probe as it is being moved down the first time.

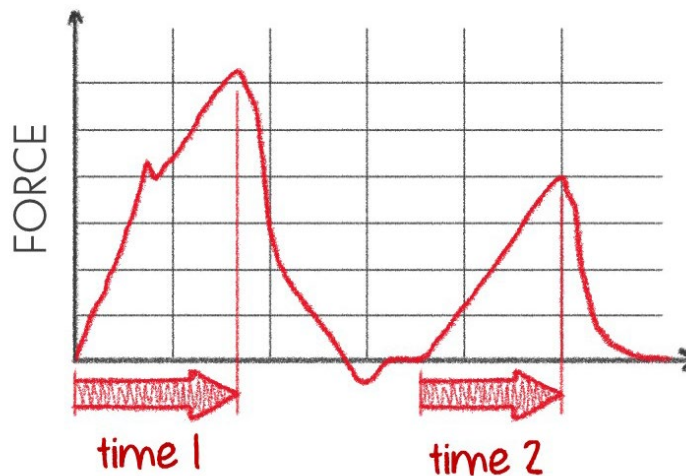


The second metric is **cohesiveness** which measures the ability of the bread to not be damaged during the test. The less damage the bread incurs, the closer the size of two areas under the force profile for each movement will be.



$$\text{cohesiveness} = \frac{\text{area 2}}{\text{area 1}}$$

The third and final metric is **springiness**, which measures the extent to which the bread returns to its original shape between each movement. This is based on the differences in times it takes for the probe to reach the same points on each movement. If the bread has not 'sprung' back, there will be a longer time of 'no force' being detected on the probe.



$$\text{springiness} = \frac{\text{time 2}}{\text{time 1}}$$

These three metrics combine to define **chewability**:

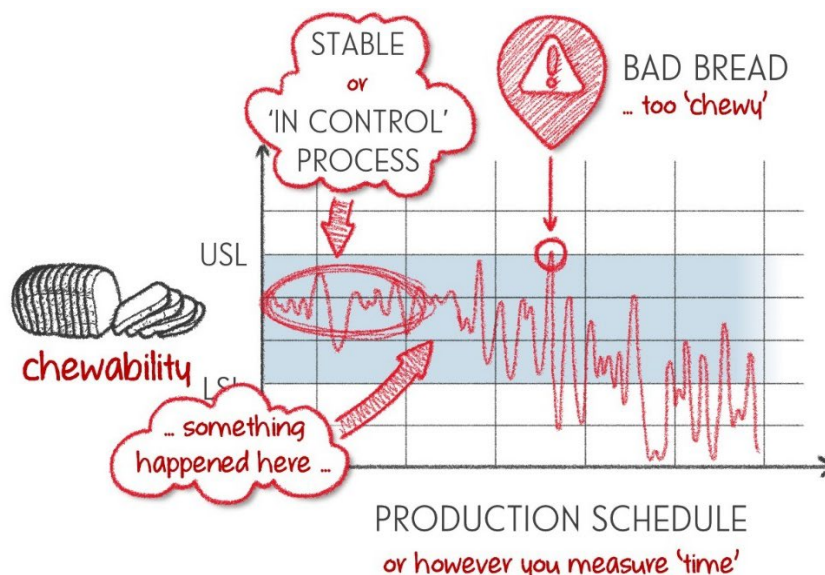
$$\text{chewability} = \text{hardness} \times \text{cohesiveness} \times \text{springiness}$$

This now allows us to objectively assess how customers and consumers will likely view the **quality** of our bread (at least in terms of **chewability**). It also allows us to easily detect changes from one loaf of bread to another ... which is an important part of keeping our **processes** in **control**.

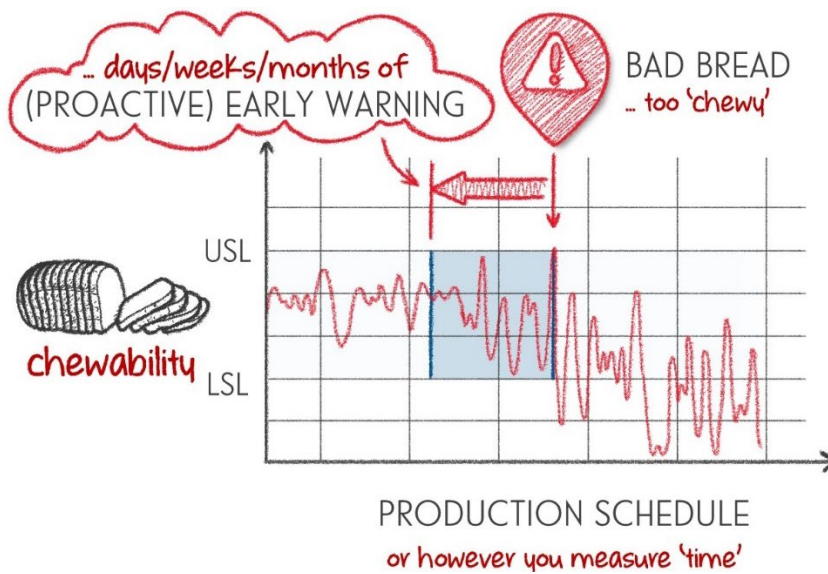
... this is where **STATISTICAL PROCESS CONTROL (SPC)** really helps

SPC means we rely on a statistic (which is a fancy title given to a **product characteristic** that is often measurable) instead of waiting for things to go bad. This means we are focusing on identifying trends that might suggest that our **process** is starting to go '**out-of-control**' and not waiting for our products to become **defective**. We will ideally bring our **process** back **under control** before any 'bad' **product** is generated.

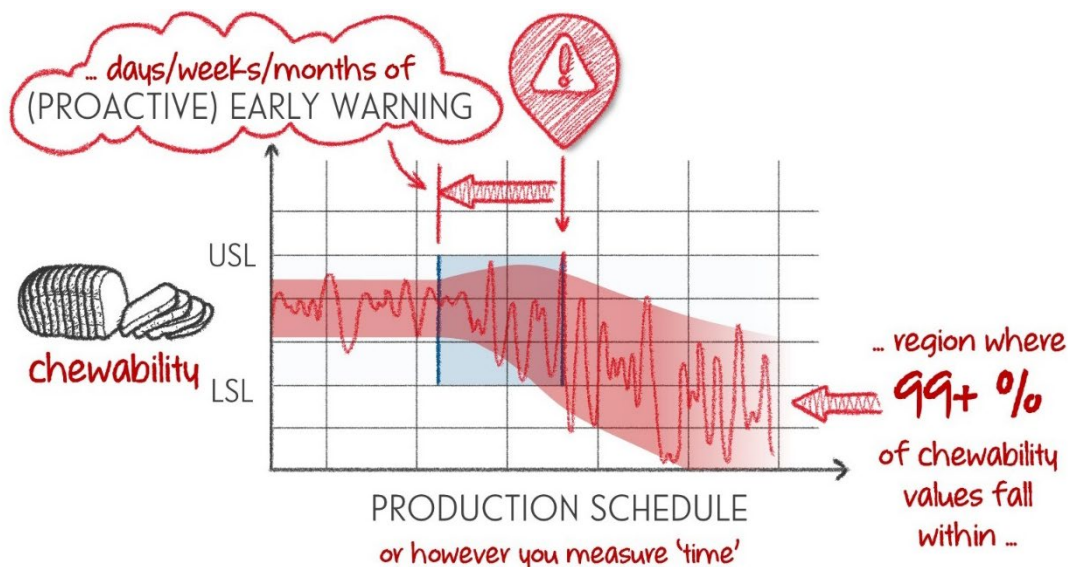
If we go back to the **chewability** of our bread over time ...



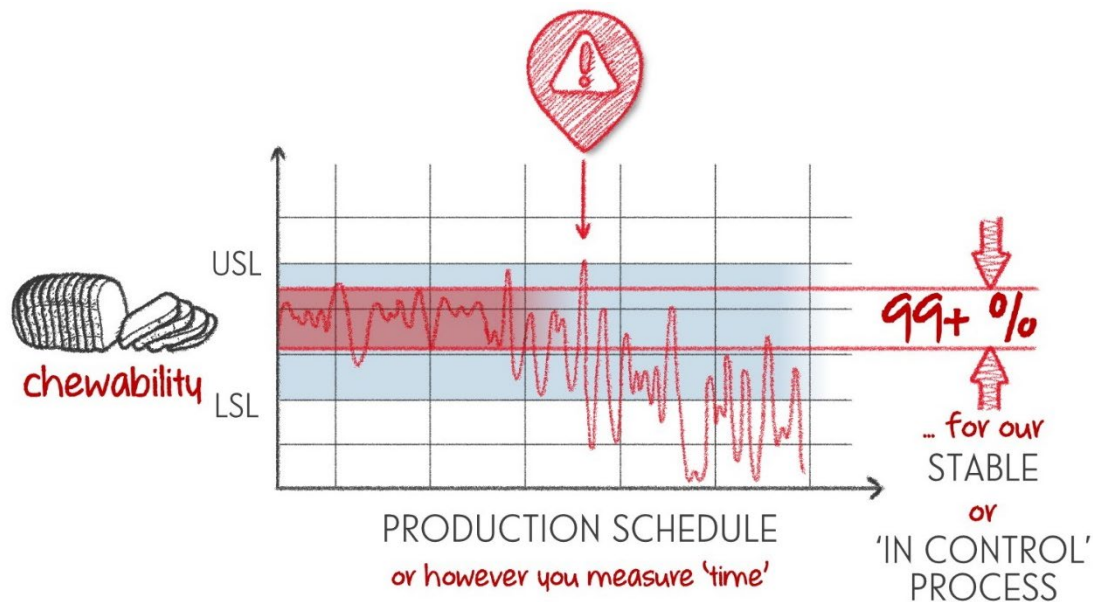
If we can do something to identify the precise moment when our process starts becoming '**out-of-control**' ...



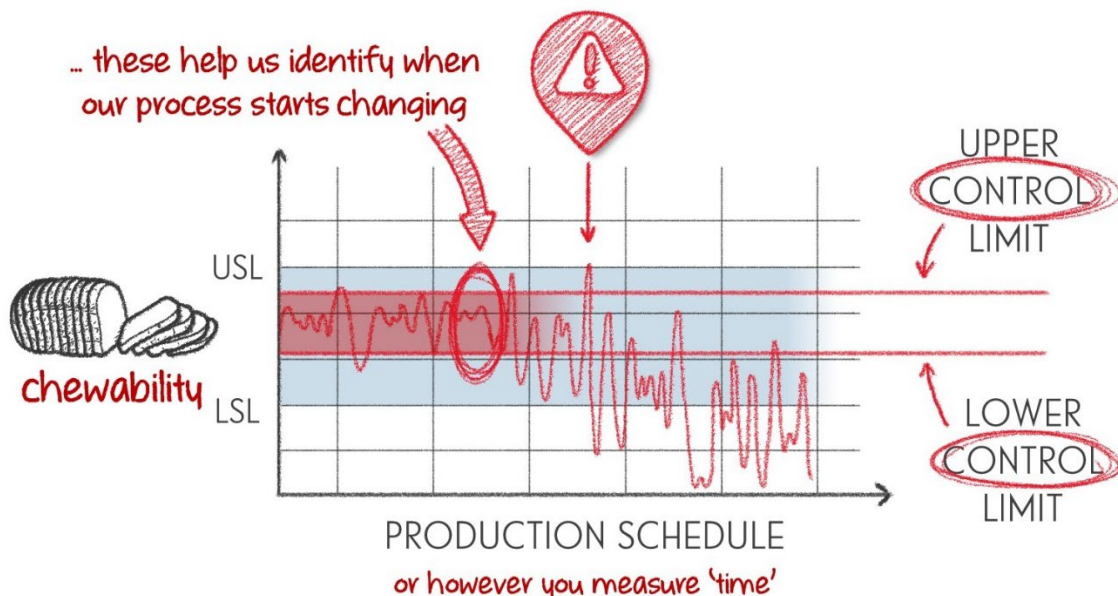
The ways in which **SPC** can identify the slightest trend or change that might signal an '**out-of-control**' **process** will be covered in greater detail later in this guidebook. But much of it comes down to a simple approach of identifying regions in which we expect the majority of our **product characteristics** to lie. For example, as our process transitions from '**in control**' to '**out-of-control**' ...



We can reverse this chart in a way, and instead work out where we expect the majority of our **product characteristics** to lie if our **process** remains '**in control**:'



We can also give the bounds within which we expect the majority of our **product characteristics** to lie IF our **process** remains 'in control.' We call these bounds the **Upper and Lower Control Limits (UCLs and LCLs)**. These are not to be confused with **Upper and Lower Specification Limits (USLs and LSLs)**. **USLs and LSLs (specification)** tell us if our **product** is defective or 'bad.' **UCLs and LCLs (control)** help us work out if our **process** is starting to become 'out-of-control.'



There are many other tools, rules, and tricks beyond identifying **UCLs** and **LCLs** to working out if our **process** is starting to become 'out-of-control.' They are not to be feared! They are simple and easy to implement. And can help you make sense of what might seem a mess of data points.

But to come up with things like **UCLs** and **LCLs** we need to **sample** our **process** while it is **in control**. We need to (for example) test the **chewability** of the loaves of bread created by an '**in control**' process to be able to gauge the region in which we expect most **characteristics** to lie.

What is a CAPABLE PROCESS?

The aim of virtually all manufacturing **quality** initiatives is to create **capable processes**.

a CAPABLE PROCESS is a process where the observed VARIATION is largely within the specification limits

And this is the focus of the next lesson.

PROCESS CAPABILITY

Remember that ...

... a CAPABLE PROCESS is a PROCESS where the observed VARIATION is largely within the specification limits ...

But this isn't very specific. Is (for example) 168.6 PPM to be outside **specification limits** OK? The answer to this question depends on every organization's unique circumstance, and every customer's unique expectations.

The organizations who 'do **quality** well' tend to be those who are not after 'yes/no' answers to the question ...

... is [MANUFACTURING QUALITY] OK?

These organizations tend to continually focus on improving **quality**, understanding which parts of their **processes** are likely to lead to instances of **poor quality**, and focusing all their efforts on the VITAL FEW parts of their process that are causing or likely to cause the most problems.

This approach sounds ridiculous to many.

Why? Because this suggests '**quality**' is a never-ending resource drain where no matter what, nothing is ever good enough. So-called 'immature' organizations demand to know 'if they are there yet' so they can stop doing **quality**. The large number of problems with this approach include the fact that because production lines age and evolve, customers find new ways of using their products, and all sorts of other unknown but reasonable challenges their products will ultimately face will see '**quality**' quickly slip. This causes production line stoppages, angry customers, warranty action, field repairs and so on.

Remember ... QUALITY is like steering a car. You can't just bolt the steering wheel in the 'right' direction and assume you will arrive at your destination. Or live.

Those organizations who have a **quality mindset** embedded into their collective decision-making tend to be able to manufacture quality products faster and cheaper than their competitors. Their competitors (who have constant problems with production efficiency and product **quality**) tend to delude themselves that high **quality**, low costs and fast production are an impossible combination.

Organizations like Toyota demonstrate this to be false.

So what is a **'high-quality' production process**?

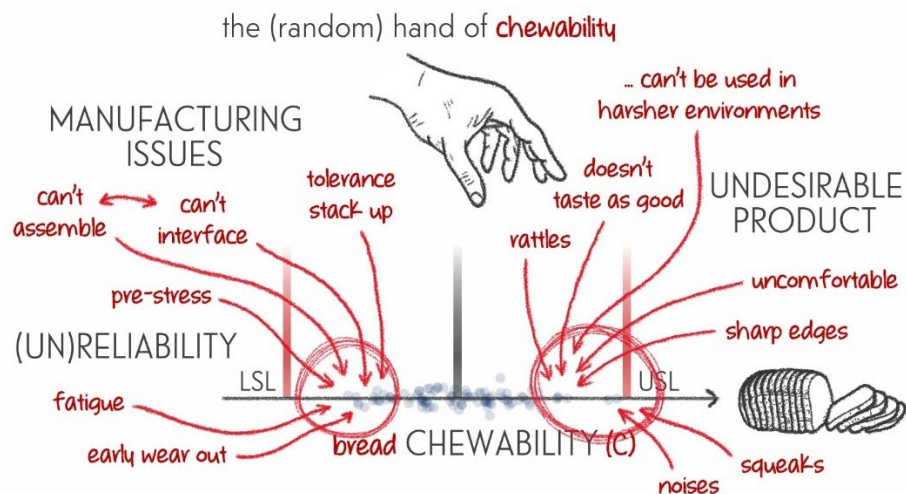
... a **HIGH-QUALITY PRODUCTION PROCESS** is a **PROCESS** that is
(1) **IN-CONTROL** and (2) **CAPABLE**.

In that order.

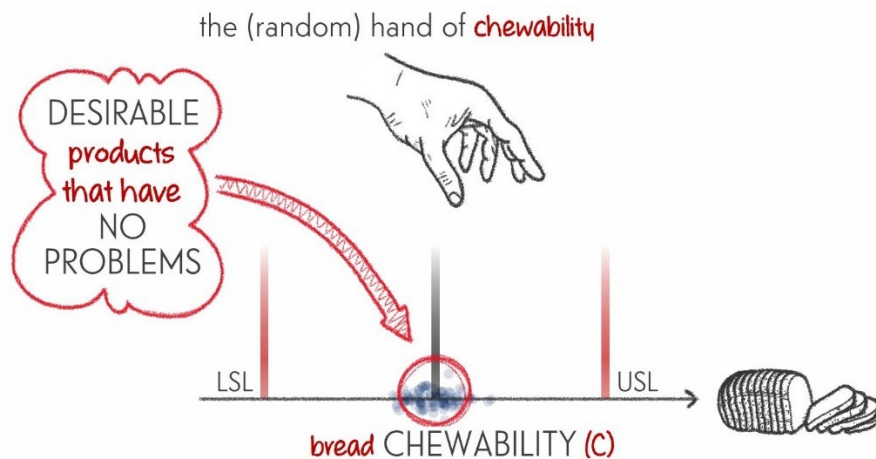
Why? If your process is **out of control**, then it is (by definition) changing, evolving or deteriorating in ways that you don't understand. This means that even if your products are within **specifications limits** now, this is down to luck and will not be the case for too much longer.

So the very first thing we need to do is to ensure that our **process** is **IN CONTROL**. And this involves tools like **SPC** to make sure that our **process** is not changing and continues to do what we expect it to do. It also means that we understand the factors that drive our **process**. What the temperature needs to be. What the speed needs to be set to. How much flour we need to add. How much time our bread needs to proof or rise.

Then ... and only then ... can we influence our system to make sure the **characteristics** of our products are within **specification limits**. For example, our bread's **chewability** (or any product's characteristic) might 'largely' be within specification limits, but ...



Instead, we want our process to look like this ...



Perhaps the most 'valuable' trait of the **process** above is that any 'hint' of **out-of-control** behaviour is very obvious very early. As variation is minimized, changes in the underlying **process** are not hidden within a cloud of highly variable data points.

This means that **capable processes** allow us to ...

... (1) be aware of potential problems in production earlier

... (2) have more time to address these problems as the variation in the natural variation in the underlying process is very small and

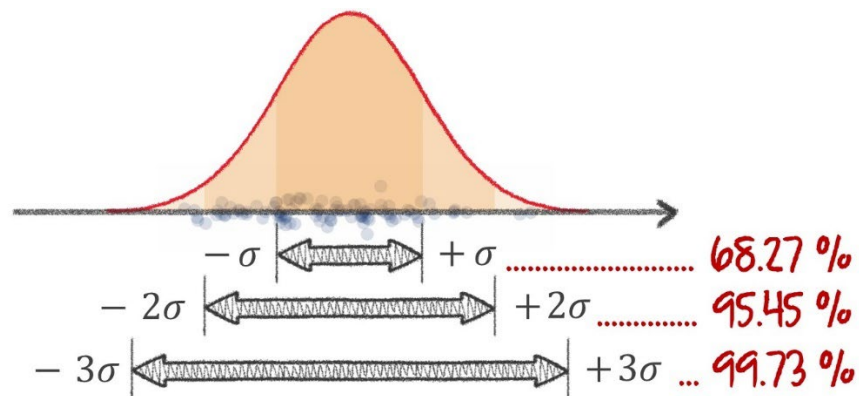
... (3) be able to address these problems in a 'less stressful' way as we are not waiting for our products to go 'outside of specification limits' before we do something.

This also means that we are not constantly panicked, fighting fires, or otherwise rushing to find the quickest and easiest 'fix' to allow production to continue. These quick and easy fixes can often be short lived as they were identified during those high stress situations where products are 'outside of **specification limits**' with a lot of pressure to 'do something.'

so how do we MEASURE CAPABILITY

In previous lessons, we looked at the CENTRAL LIMIT THEOREM and how it relates to the NORMAL DISTRIBUTION. That is, if a **random process** involves the aggregate or summing of lots of other **random processes**, then the outputs of that random process tend to be described by the **bell curve** (or normal distribution). For this reason, we often see the **normal distribution** in manufacturing and production scenarios. However ... this is not ALWAYS the case.

If we can confirm that our **production process** is well described by the **normal distribution**, this means that the random nature of key product characteristics are described by a **bell curve**. And from previous lessons we know ...

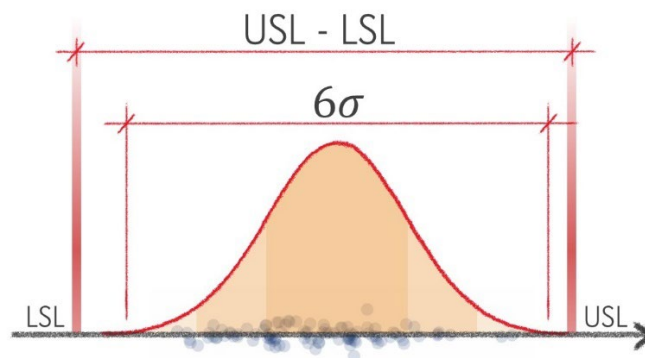


Remember that ' σ ' is the **standard deviation** of the **bell curve**, which is a **parameter** that captures the '**dispersion**' or '**variation**' of **random variable values**. Most 'standard' ways of measuring **capability** rely on an assumption that the characteristics in question are described by this **bell curve**.

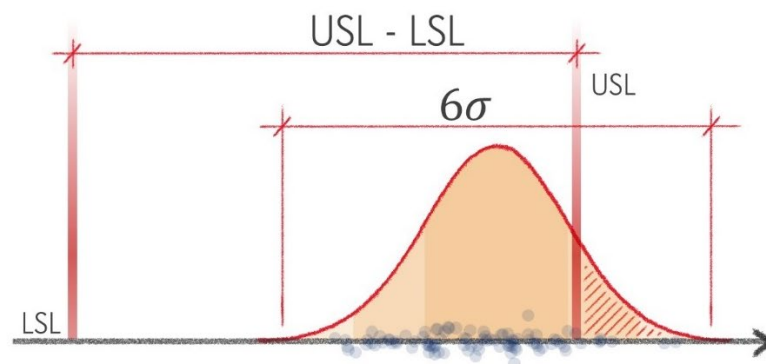
Capability indices are quantitative ways of relating the natural variation of these characteristics to **specification limits**. One **capability index** is C_p .

$$C_p = \frac{USL - LSL}{6\sigma}$$

For our **random process** below, $C_p = 1.18$.



This **capability index** essentially characterizes the extent to which **variation** compares to the 'range' between **USL** and **LSL**. But there is a problem with this because the **process** below also has a $C_p = 1.18$.



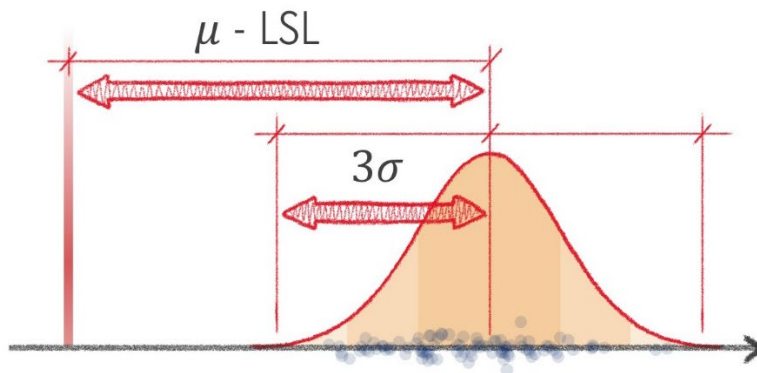
With the same **capability index** (C_p), the second process clearly has many more defective products. So C_p is not a particularly useful **capability index** (... but we talk about it here because it appears in a lot of guidebooks and textbooks and you will need to have a general knowledge of it).

A much more useful **capability index** is C_{pk} ...

$$C_{pk} = \min \left[\frac{(\mu - LSL)}{3\sigma}, \frac{(USL - \mu)}{3\sigma} \right]$$

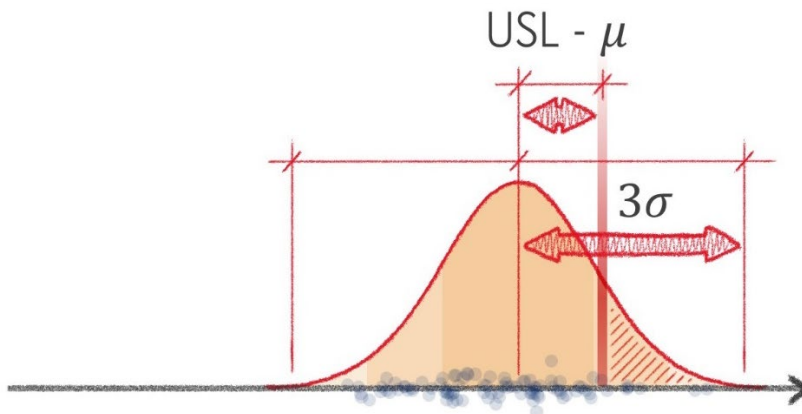
This **capability index** takes into consideration both the **variation** AND the **mean** of the random variables. So for the process above, we start by calculating ...

$$\frac{(\mu - LSL)}{3\sigma} \dots = 1.97$$



We then calculate ...

$$\frac{(USL - \mu)}{3\sigma} \dots = 0.37$$



So for the process below, we take the smallest value of the two we just calculated ...

$$\begin{aligned} C_{pk} &= \min \left[\frac{(\mu - LSL)}{3\sigma}, \frac{(USL - \mu)}{3\sigma} \right] \\ &= \min[1.97, 0.37] \end{aligned}$$

PROCESS PERFORMANCE GOALS

So what should we be 'aiming' for when it comes to our **processes**? Where do we need to be?

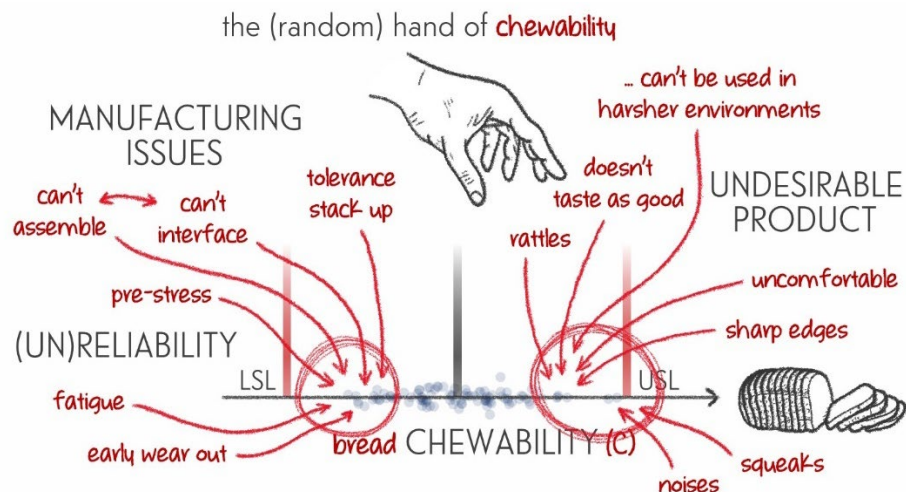
We have previously talked about how there is no such thing as 'good' and 'bad' when it comes to **processes**. There is no (or shouldn't be a) binary approach. We can use things like **capability indices** to help us come up with a number, allowing us to compare one **process** to another.

So the reason we need to come up with **performance** goals for EACH CHARACTERISTIC is to be able to compare the RELATIVE CAPABILITY of each **performance attribute**. Those **processes** that meet or exceed the aim are the TRIVIAL THOUSANDS we don't need to focus on. The remaining **processes** that DON'T meet the aim are those VITAL FEW that we need to improve. And if every **process** meets the aim ... then there will always be a process that is the 'weakest' link. And to keep your overall production '**high quality**,' that is the **process** we need to focus on.

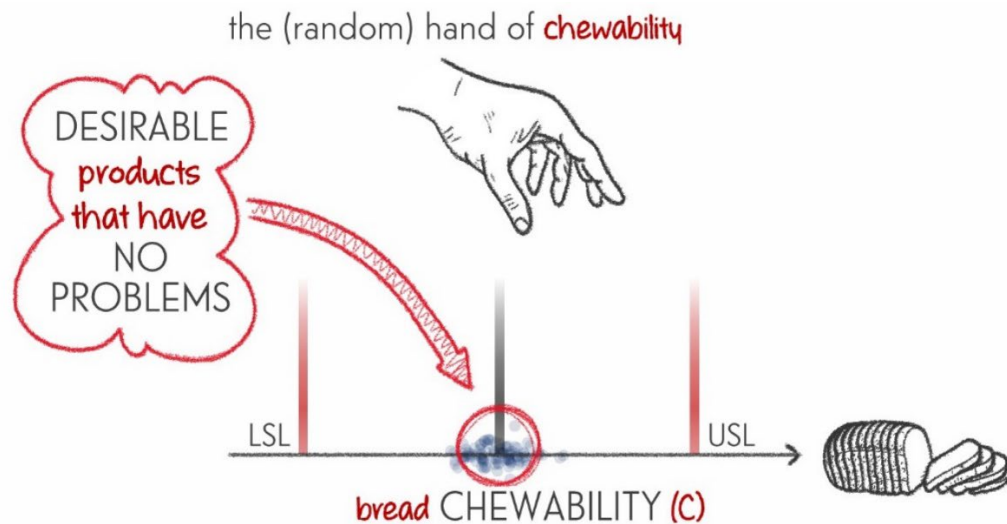
This is where we start to save time and money. We don't want to try and improve everything. If we know the 'weakest link,' then we only need to focus on that part of our production system to maintain **high quality**.

It is never a question of 'are we there yet?'

So we don't want our **process** to produce **products** like this ...

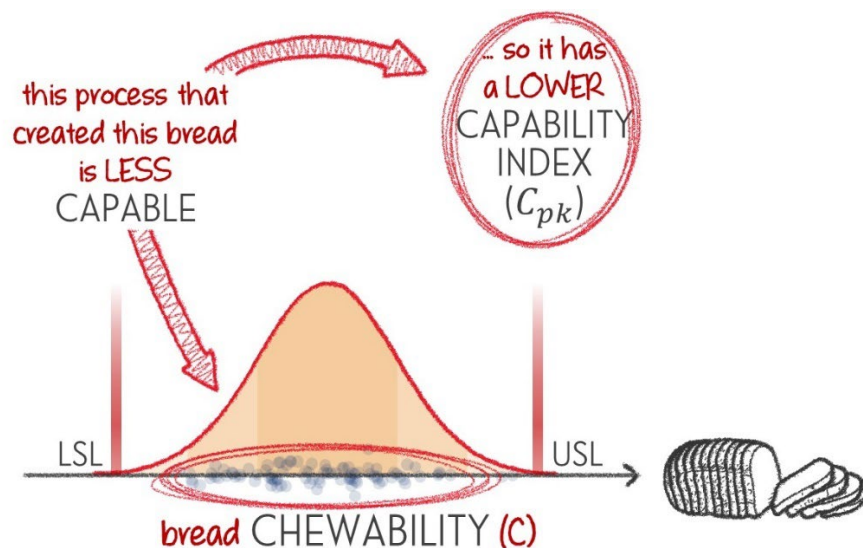


Instead, we want our **process** to look like this ...

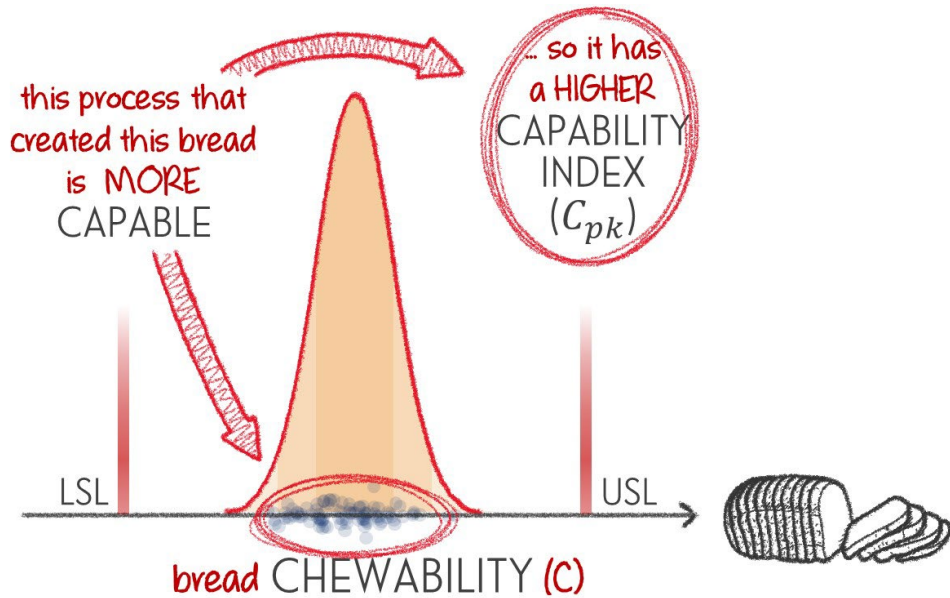


But perhaps the most 'valuable' trait of the **process** above is that any 'hint' of **out-of-control** behaviour is very obvious very early. As variation is minimized, changes in the underlying process are not hidden across a range of data points.

Our first process that has all those problems even though the observed data points are all within **specification limits** has a lower **capability index**.



Our second **process** which has few, if any issues has a higher **capability index**.



There are some VERY BASIC guidelines regarding **capability indices**.

C_{pk}	two SPECIFICATION LIMITS	one SPECIFICATION LIMIT
not CAPABLE	< 1.00	< 1.00
barely CAPABLE	1.00	1.00
existing process	1.33	1.25
new process	1.50	1.45
safety-related existing process	1.50	1.45
safety-related new process	1.67	1.60
6σ quality process	2.00	2.00

These are arbitrary and should not be blindly applied to YOUR ORGANIZATION. They are useful for getting an idea of 'where you are at' in terms of maturity and the art of the possible. But you need to understand what goals apply to your product.

What is the next step?

Learning more about **SPC and PCA**. This was an introduction that focuses on WHY you should do **SPC and PCA**, and what you would expect to achieve. Too many engineers rush to the next (statistical) bit first without ever understanding what they are trying to achieve.

SPC is all about getting the earliest possible warning that your process is starting to come **out of control**. The earlier you get this warning, the more time and less stress you have to solve the underlying issue before it ever becomes a problem that results in defective products.

PCA is all about using the data you gather as part of **SPC** to work out if your product is going to meet **allocated quality goals**. We can create capability indices that our manufacturing team can work towards to 'know' that the product will be of high enough quality.

The alternative is wait until something goes wrong to trigger a crisis in your organization that requires 'all hands on deck' to come up with the quickest (and usually least effective) solution in order to start production again. Which of course means it won't be long before your next crisis. All of which costs time and money. And generates plenty of blame.

Which organization would you prefer to work in?