

What is Statistical Process Control (SPC)?

Hint ... it helps keep your AMAZING processes AMAZING ...



WORKBOOK

Presented by

Dr Chris Jackson

Reliability engineer



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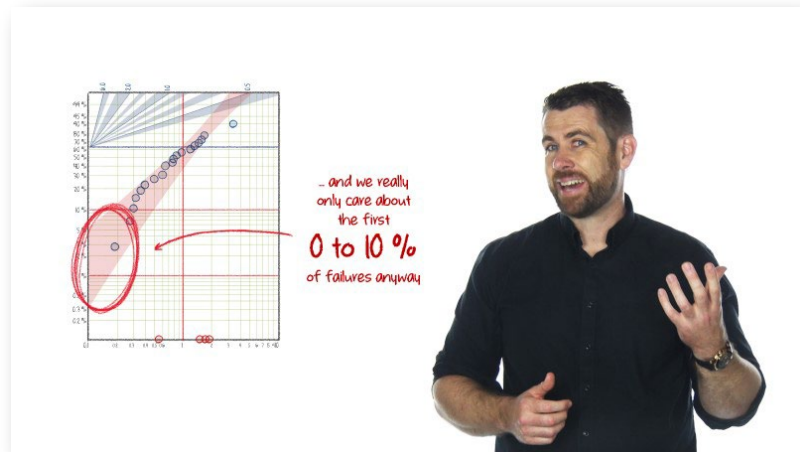
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Who is your teacher? ... Dr Chris Jackson

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.

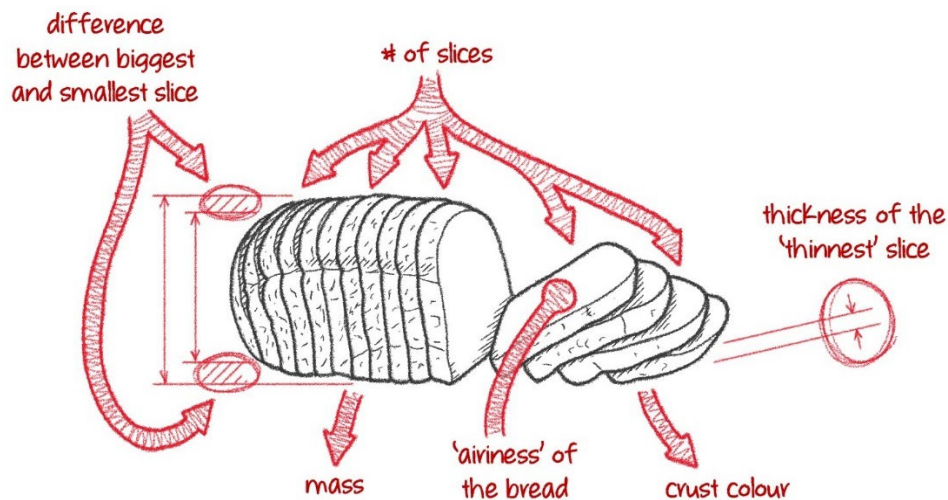
So what can we do to protect ourselves from **processes** that stop doing what we want them to do? This is a very light introduction into how we can '**control**' **processes** so that they stay well within the bounds of what we call 'acceptable.' And the driving principle behind this is PROACTIVITY. 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.

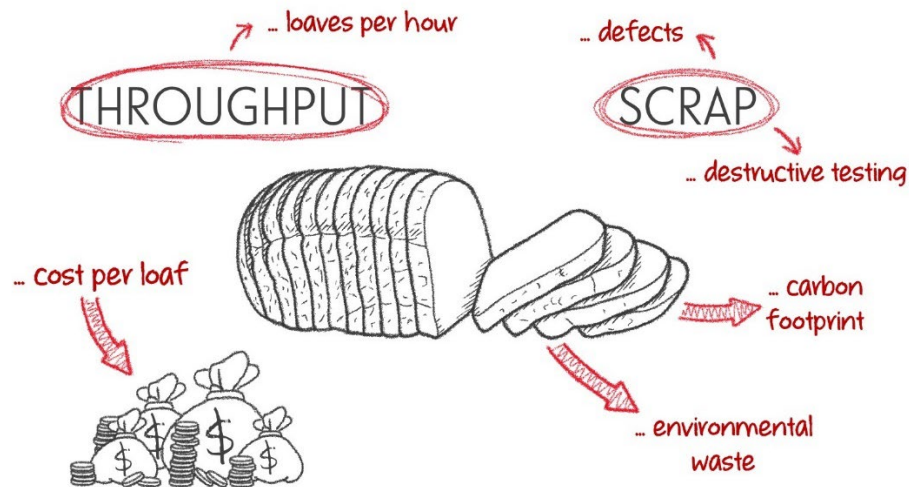
As is the case for most things in life, the **quality** of slice bread can be measured in many ways. A small selection of 'sliced bread characteristics' are illustrated below.



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 ...

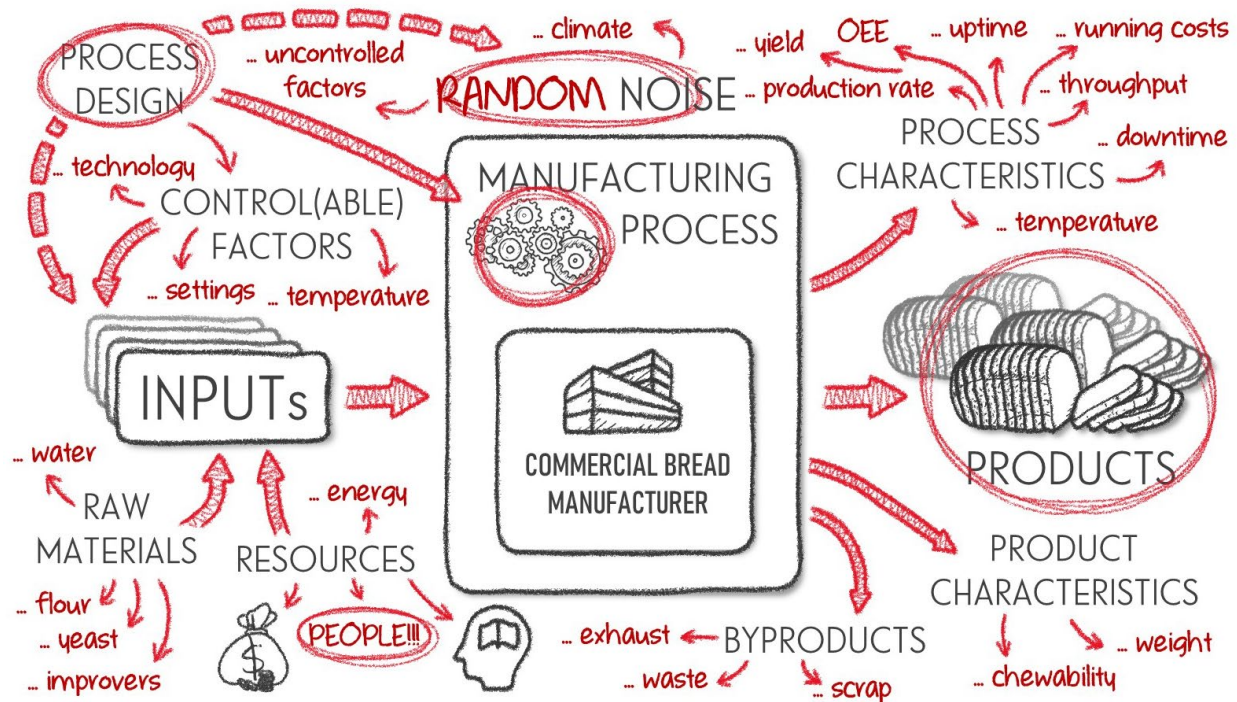


bread doesn't **GENERATE VALUE** ...
... the **PROCESS** that makes bread **GENERATEs VALUE**

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.



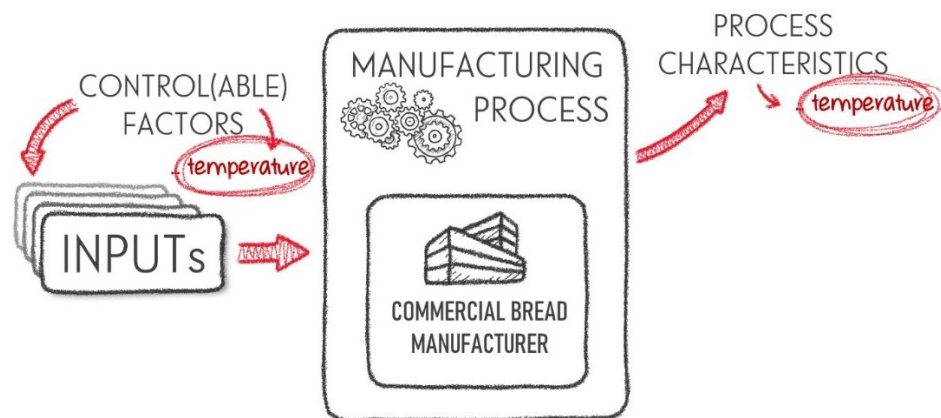
On the left-hand side of the diagram above are **inputs**. There are lots of (slightly and not so slightly different) interpretations of 'common definitions' when it comes to **process design** – particularly manufacturing. **Inputs** generally cover 'everything' that is provided to a **process** – but 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).

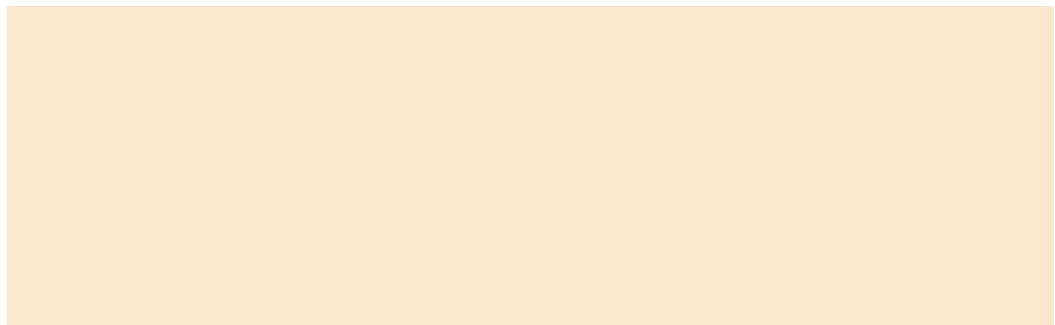
But there are also other things that our **process** creates. We call these **by-products** and include things like exhaust (such as CO₂ emissions), waste and scrap. **By-product characteristics** tend to be considered **process characteristics** (such as amount of exhaust create per operating hour).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

EXERCISE

You might have noticed on the commercial bread making diagram on the previous page that 'temperature' appears as both a **CONTROLLABLE FACTOR** and a **PROCESS CHARACTERISTIC**.



How can this be?



Keeping an AMAZING PROCESS AMAZING

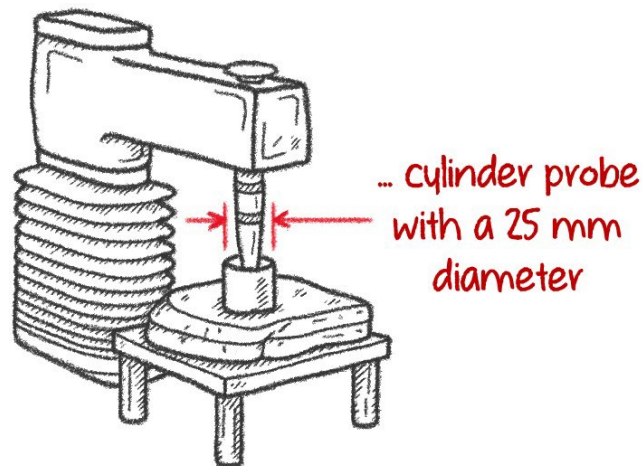
It often seems difficult to measure what can be subjective things in an objective way. For example ...



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.

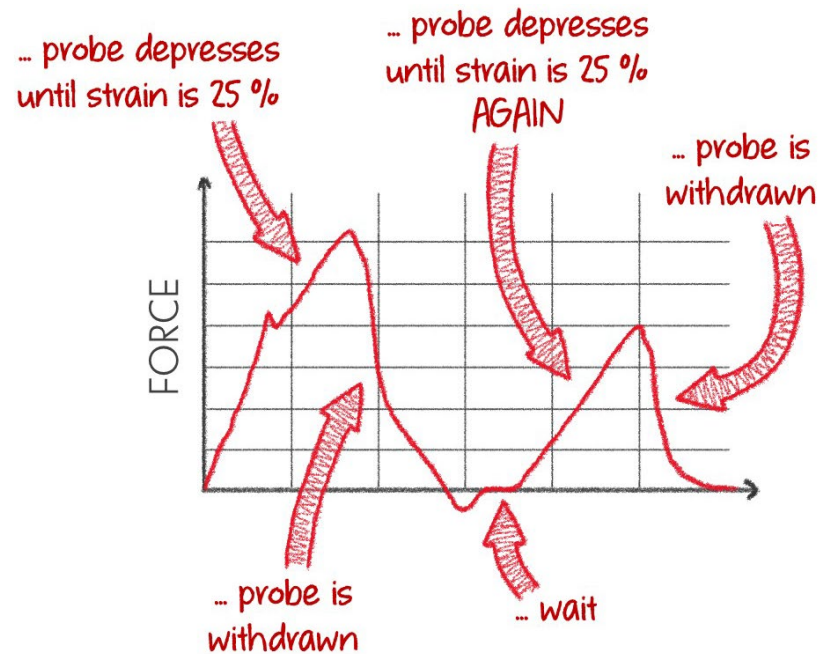
We NEED to measure what we NEED to measure. Not what is EASY to measure.

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.

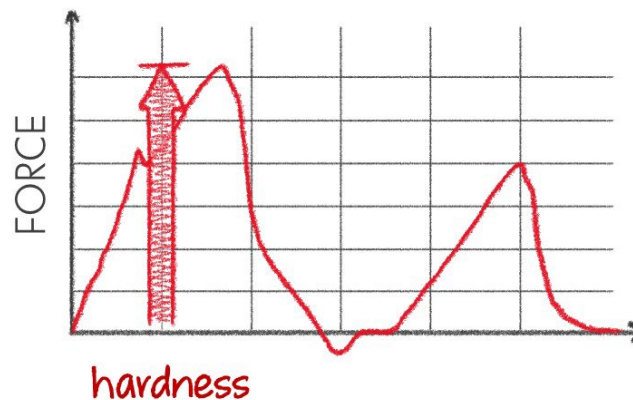


The texture analyzer has the ability to very slowly move an attached probe up and down and measure the smallest of forces that the probe experiences. In the illustration above, two slices of bread are being tested together.

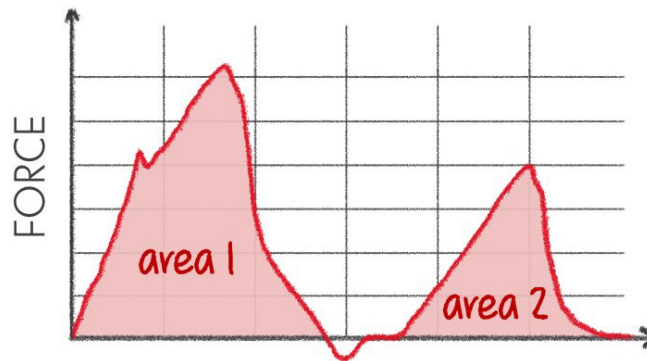
The 'standard' test for bread **chewability** involves the probe being moved down into the bread and out again ... twice. This creates force profile like the one illustrated below.



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.

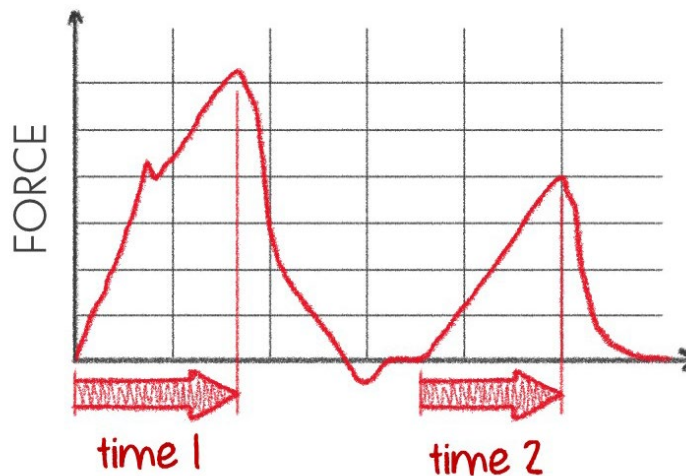


The second metric is **cohesiveness** which measures the ability of the bread to not be damaged during the test. The less damage the bread incurs, the closer the size of two areas under the force profile for each movement will be.



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

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**:

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

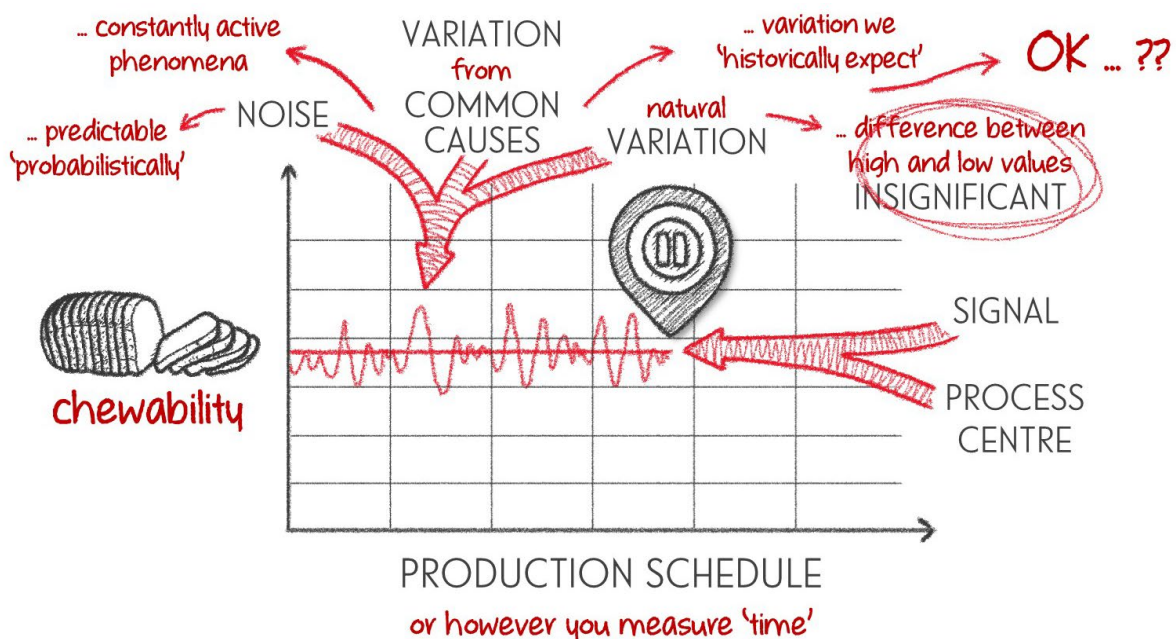
This now allows us to objectively assess how customers and consumers will likely view the **quality** of our bread (at least in terms of **chewability**). It also allows us to easily detect changes from one loaf of bread to another ... which is an important part of keeping our **processes** in **control**.

processes over TIME

Which brings us back to one of the points that was made earlier ...

... all processes WILL change, evolve, age and deteriorate ... which means we need to continually fight to retain control.

A useful way to represent how things change over time is by plotting **product characteristics** (like **chewability**) against however you measure progress on your production schedule using a chart like the one below.



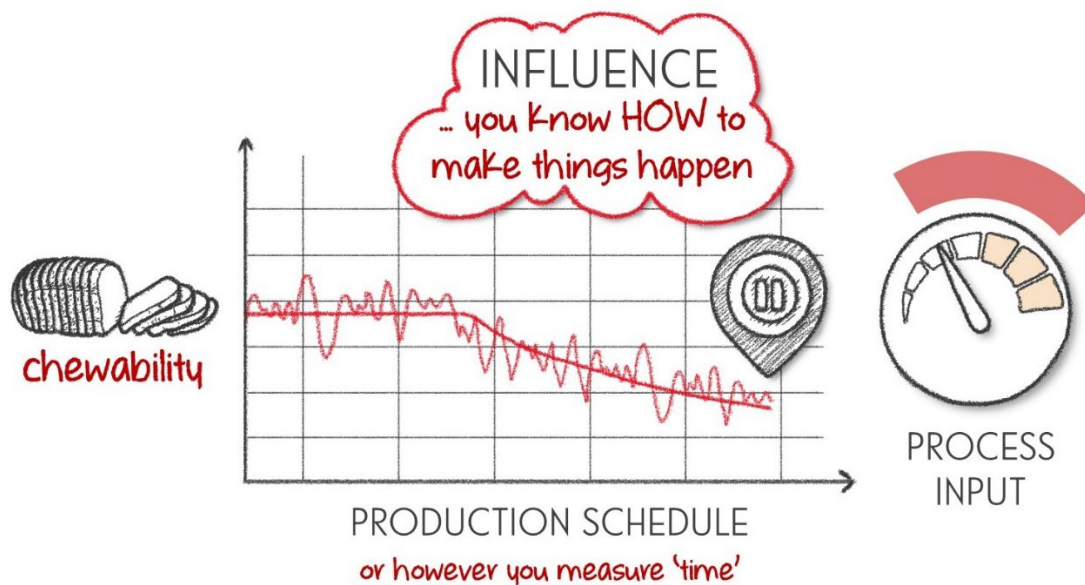
We can see two main elements of how our bread's **chewability** changes over time.

The first is called many things ... **natural variation**, **noise**, or **variation from common causes**. These refer to the same thing – the inherent fluctuations in our **product characteristics** that we know, anticipate, understand and are happy with. All practical **processes** are **random**, and it is not possible to expect that there will be no deviation in **product characteristics** (like **chewability**) from **product** to **product** (loaf to loaf).

The second element of the chart on the previous page is also called multiple things ... like **signal** or **process centre**. This represents the 'central tendency' or typical value of the **product characteristic** we are monitoring. If our **process** is '**in control**' then we would expect that things like the 'typical' value for **chewability** to be consistent throughout production (once **natural variation, noise** or **variation from common causes** have been taken into consideration).

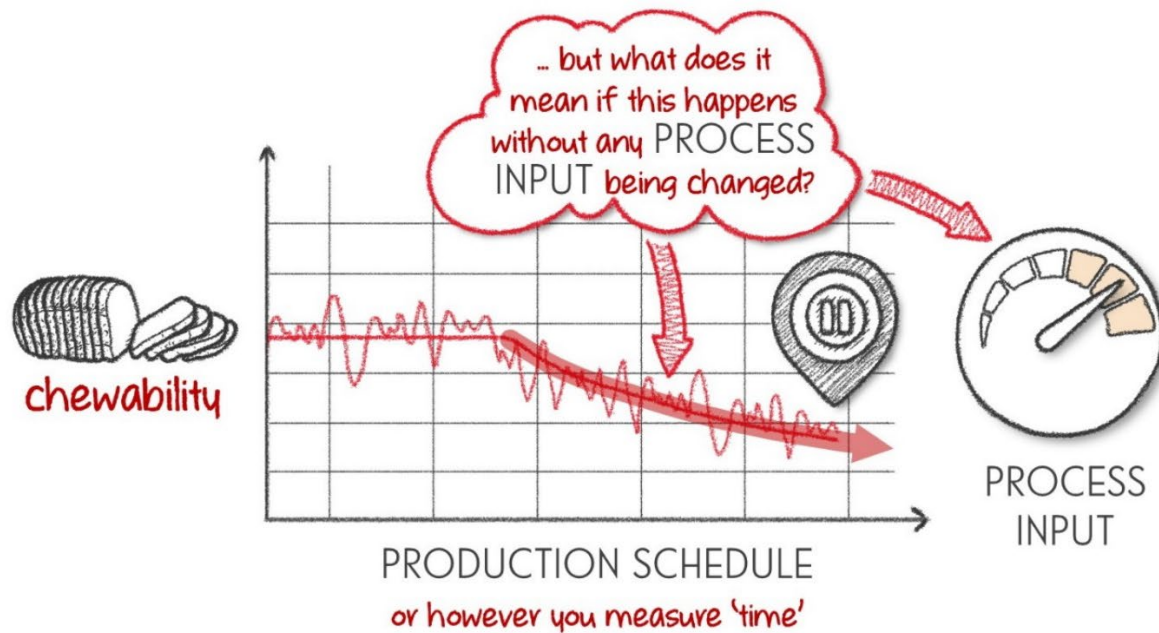
INFLUENCE

One of the key tenets of being '**in control**' of your process is **influence**. **Influence** means you know **HOW** to change the **outputs** of your **process** and have the capability to make these changes. For example, let's say that our chief baker believes that the bread **chewability** is too high. He or she no doubt knows the baking process very well. So they might 'turn down' one of the **process inputs** (temperature, speed, time, humidity, yeast content et cetera) to affect a **product characteristic** like **chewability**.

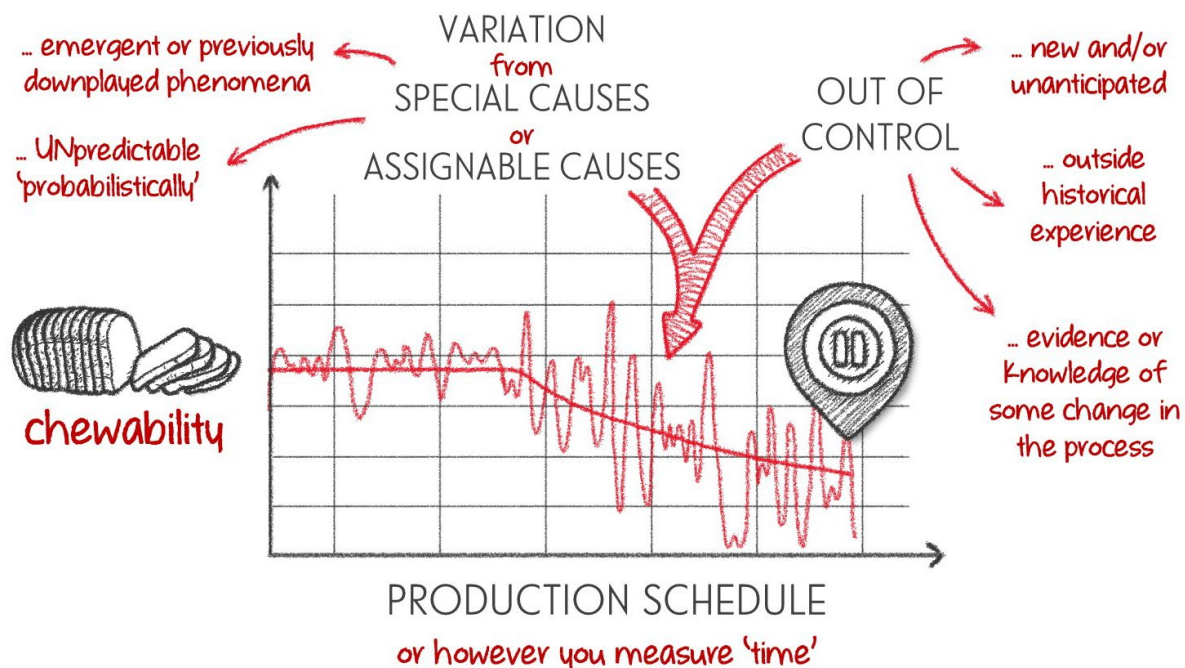


In this case, changing the **process input** has had the desired effect of lowering the **signal** or **process centre** as it relates to the **chewability** of our bread.

What you don't want is for our **process signal** or **centre** to start changing without us (knowingly) doing anything to make that happen.

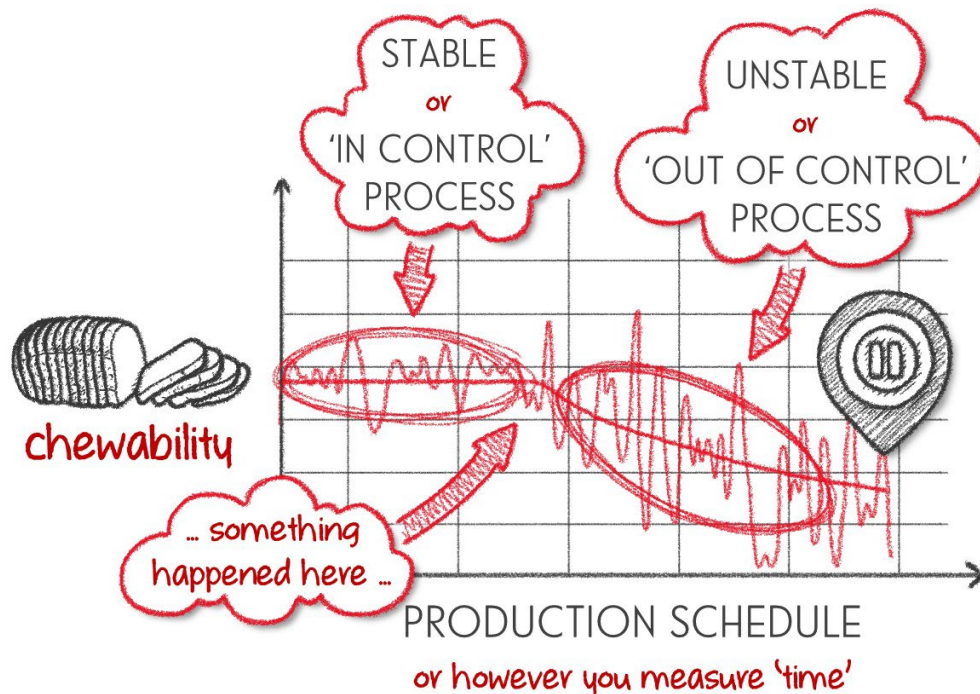


This is (by definition) an **'out-of-control' process**. It is doing something we didn't intend for it to do, and our current ways of **'controlling'** it start to fail. This could be for many reasons that range from equipment ageing through to operator complacency.



Any changes in our **'out-of-control'** processes are referred to as **variation from special or assignable causes**. These are the enemy of processes.

These charts are exceptionally useful ... and there is something that should be apparent straight away. We can actually SEE the point where our **process** ceased being 'stable' or 'in control' and become 'unstable' or 'out-of-control.'

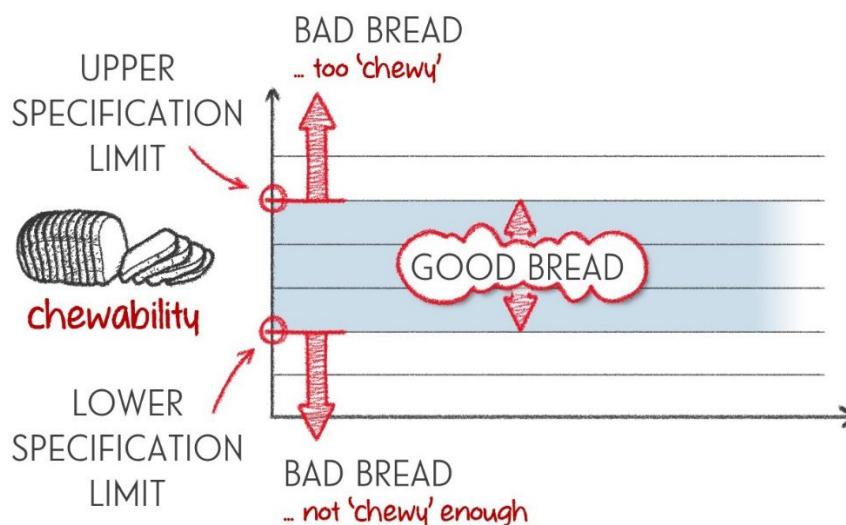


This is a very important revelation. **Statistical Process Control (SPC)** is a group of activities that help us identify the precise moment our system starts becoming 'unstable' or 'out-of-control.' And **SPC** (when done well) lets us know straight away when something happens. **SPC** involves looking at charts like the one above and realizing that something happened before our 'unstable' or 'out-of-control' process goes 'really bad.' And by doing this, we (ideally) never have to worry about our **product characteristics** ever not meeting **specifications** or **requirements** as we constantly fight to keep our **processes in control**.

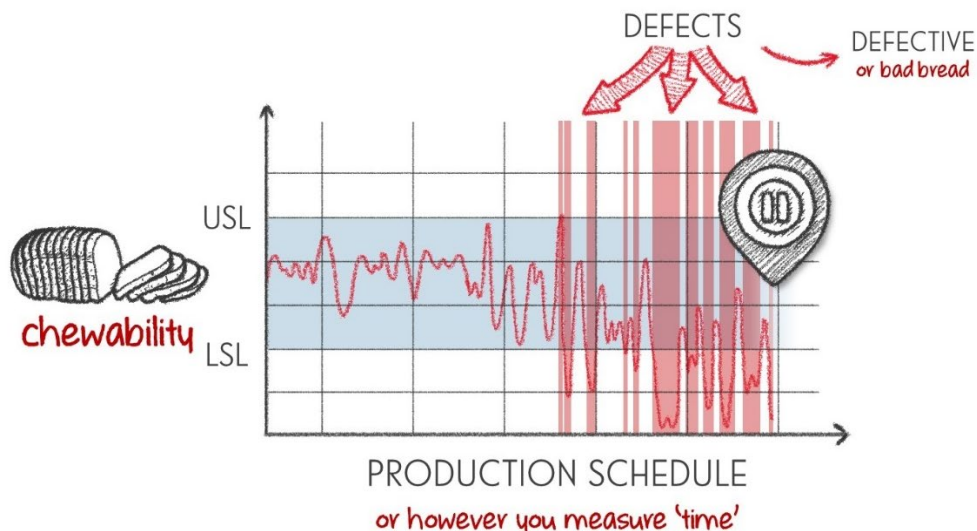
so when does OUT-OF-CONTROL transition to BAD?

From one perspective, any **out-of-control process** is 'bad.' However, our **product** often has **specifications** or **tolerances** that become not only the goals of our **process** but the arbiter of what 'good' or 'bad' is.

Let's suppose that it is possible for bread to be 'too chewy' or 'not chewy enough.' This means that we have **bilateral** or **two-sided specifications** on what 'good' bread. The maximum allowable value a **product characteristic** (like **chewability**) can have is what we call the **Upper Specification Limit (USL)**. The minimum allowable value a **product characteristic** can have is what we call the **Lower Specification Limit (LSL)**.



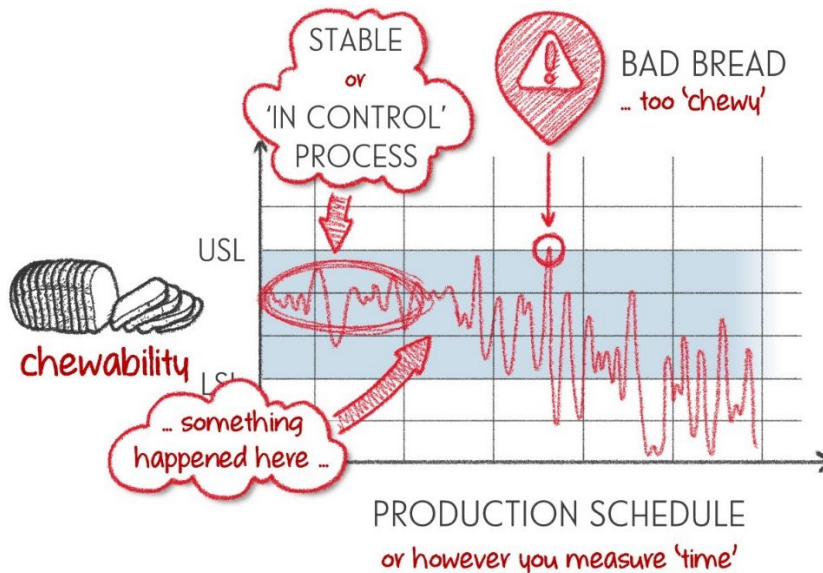
This now allows us to identify not only when our **process** is 'out-of-control' but when it leads to **defective** or 'bad' bread.



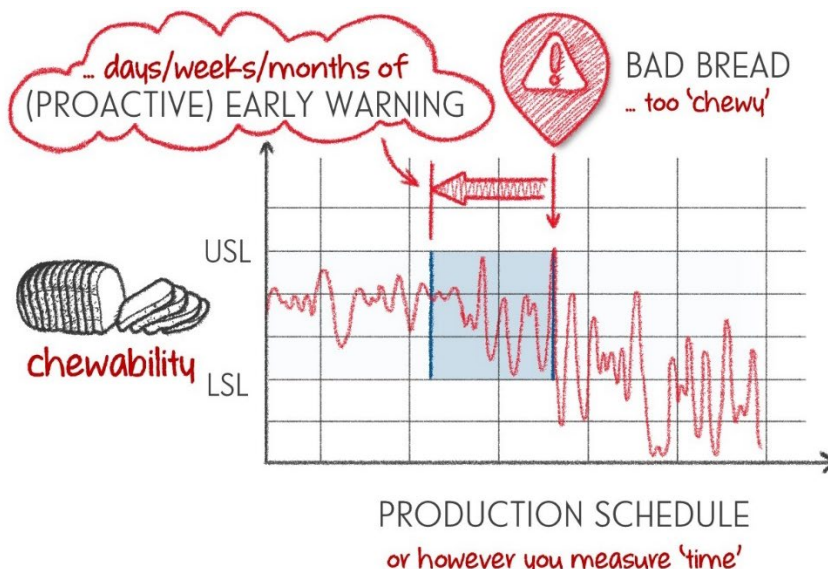
... this is where **STATISTICAL PROCESS CONTROL (SPC)** really helps

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.

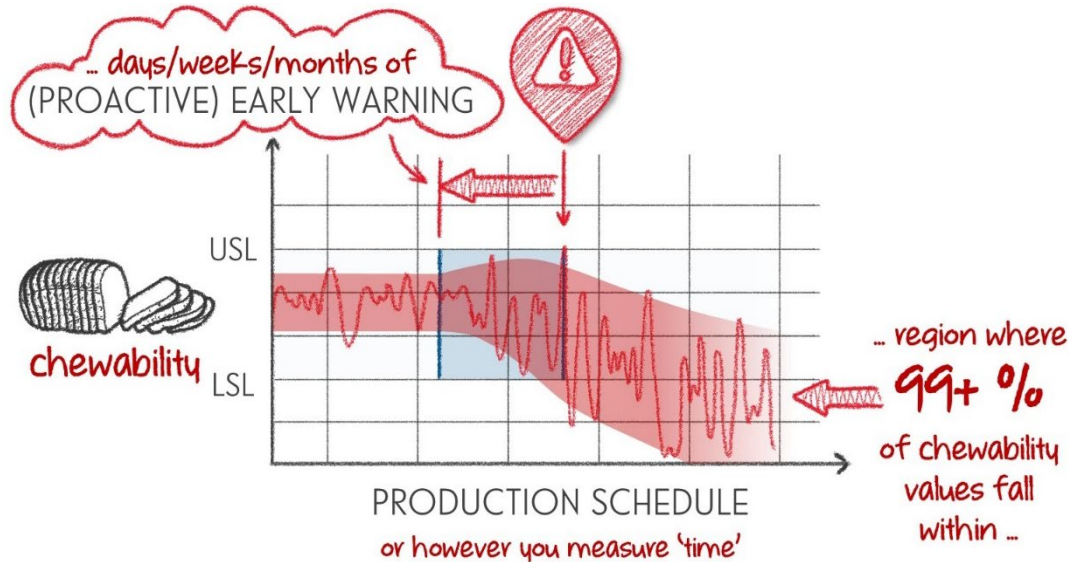
If we go back to the **chewability** of our bread over time ...



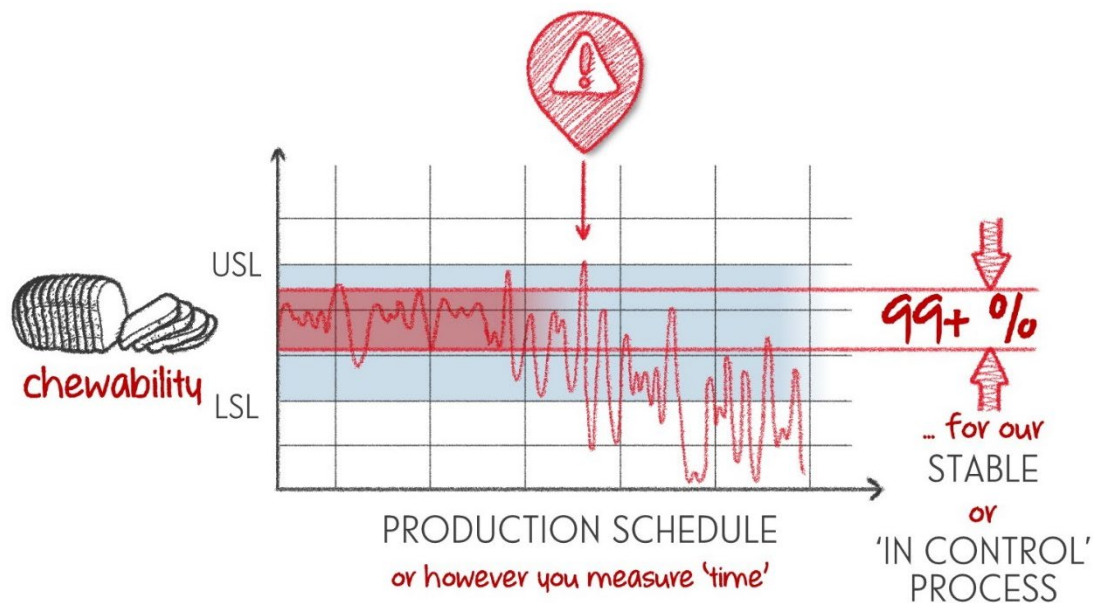
If we can do something to identify the precise moment when our process starts becoming '**out-of-control**' ...



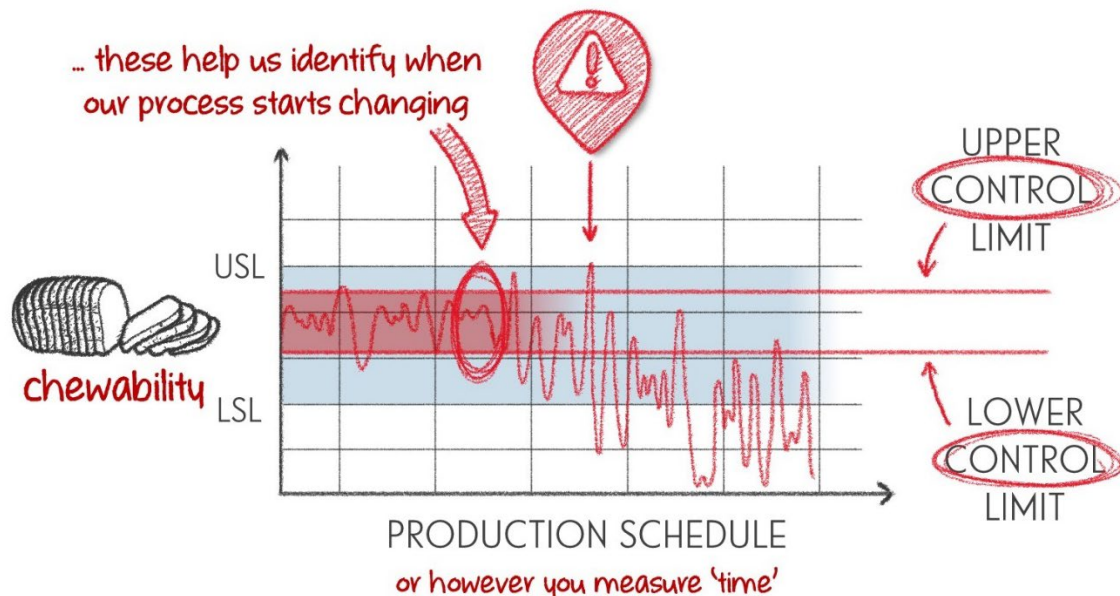
The ways in which **SPC** can identify the slightest trend or change that might signal an '**out-of-control**' **process** will be covered in greater detail later in this guidebook. But much of it comes down to a simple approach of identifying regions in which we expect the majority of our **product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



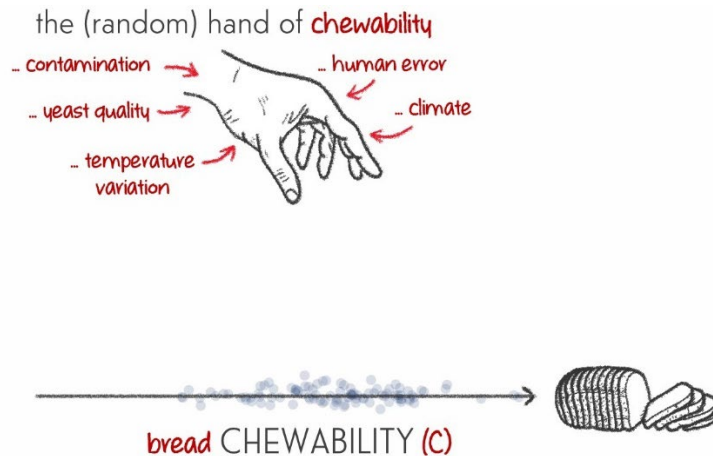
There are many other tools, rules, and tricks beyond identifying **UCLs** and **LCLs** to working out if our **process** is starting to become '**out-of-control**.' They are not to be feared! They are simple and easy to implement. And can help you make sense of what might seem a mess of data points.

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.

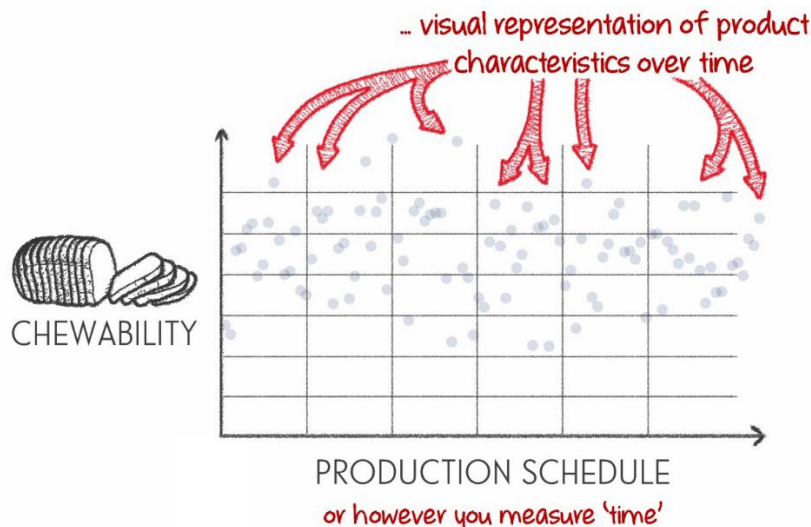
And for that ... we need a **sampling strategy**.

plotting STATISTICS from left (young) to right (old)

In many parts of this course, we have looked at **random variables** (such as **product characteristics** like bread **chewability**) on a horizontal axis. This is really helpful when we are trying to visualize the random nature of something WITHOUT thinking about how it changes over time.



But as we mentioned above ... we want to TRACK changes over time. So after we change the way we represent the metric from the horizontal to the vertical axis AND then use that horizontal axis to represent time, we get the following type of chart:



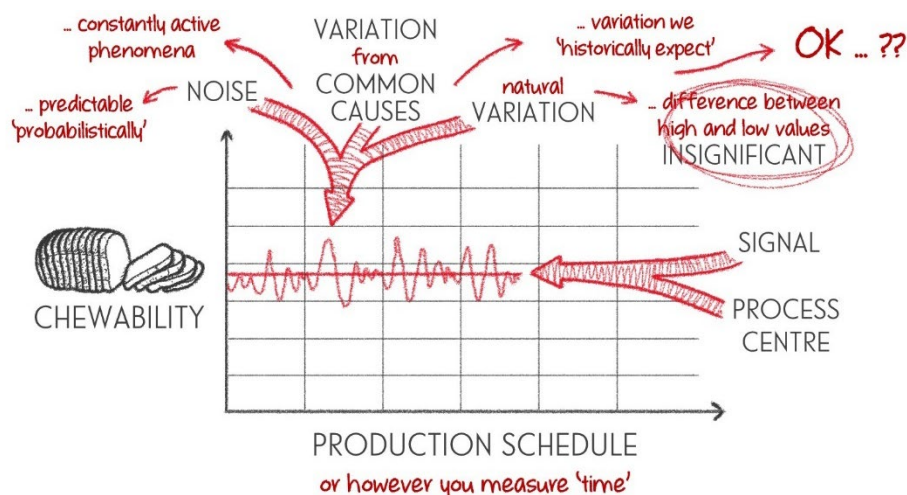
Now we can see how the **chewability** of our bread changes as the production schedule moves on. It is possible to use certain approaches and techniques to look at the seemingly disorganized spread of data points to work out if our process is **LIKELY in-control** (or not).

this is what we call a CONTROL CHART

a **CONTROL CHART** is a graph used to study how a **PROCESS CHARACTERISTIC** changes over time

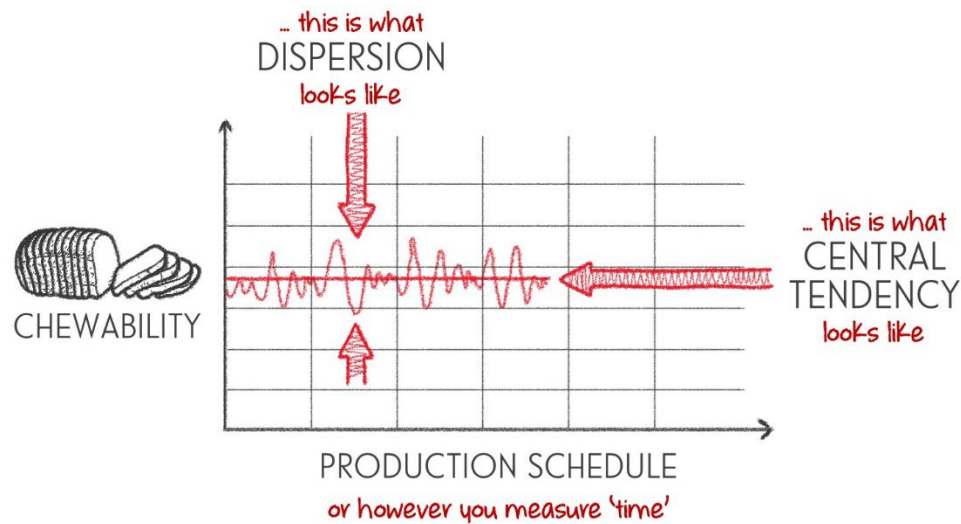
Technically, any chart that you create that essentially represents some aspect of a **process** (or **product**) **characteristic** on the vertical axis and time on the horizontal axis is a **control chart**. That being said, there are a number of 'standard' **control chart** frameworks that have been shown to be very, very useful for working out if our process is **LIKELY in-control** (or not).

This course has already covered several **control charts** (even if they were never called **control charts** at the time). The **chewability** chart below is one such example.



There are two main elements of the process that this chart represents. The first is the **signal** or **process centre**. The second is the **noise**, or **(natural) variation** that emanates from what we refer to as **common causes**. These are inherent factors that drive random behaviour in our process that we are essentially 'OK' with. An **in-control process** will have a **signal** or **process centre** that either stays the same or only changes when we want it to. For example, we can increase the **chewability** of our bread by increasing certain constituent elements of our flour.

From a statistical perspective, these two elements represent what we call **dispersion** and **central tendency**. Most **control charts** involve visually depicting these two characteristics of a random process.



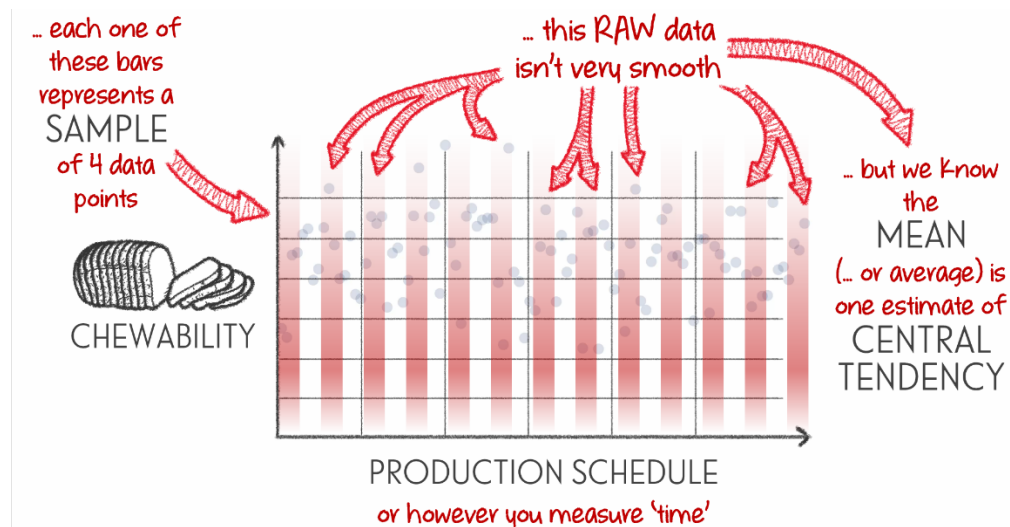
So the challenge now becomes turning what might look like an incoherent spread of data points into a simple **control chart** that allows us to easily get an idea of **dispersion** and **central tendency**.

If we focus on **central tendency** first, we know that the **MEAN** or arithmetic average is perhaps the most common way we represent a 'typical' or 'central' value of something. We sometimes talk about the 'average' height of people. We sometimes use the phrase Mean Time Between Failure (MTBF). We often start sentences with ...

... on average – [insert observation here] ...

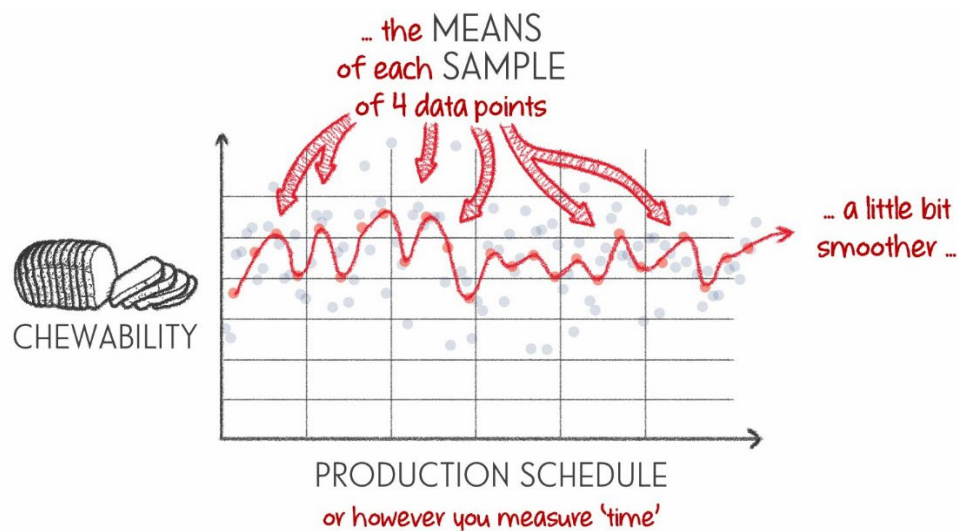
So the **mean** is often used to help us track the **central tendency** of a process. But ... we need to track this **central tendency** OVER TIME. So we can't just find the **mean** of the entire process. That won't tell us if our process characteristic is going, down, cycling, or doing anything else we might want to know about. That is why **SPC** often relies on **interval sampling** where (for example) five components of each batch, or four loaves of bread are inspect or examined every hour for key product characteristics.

Look at the (not very smooth) data below - the red bars represent **samples** that contain 4 data points.

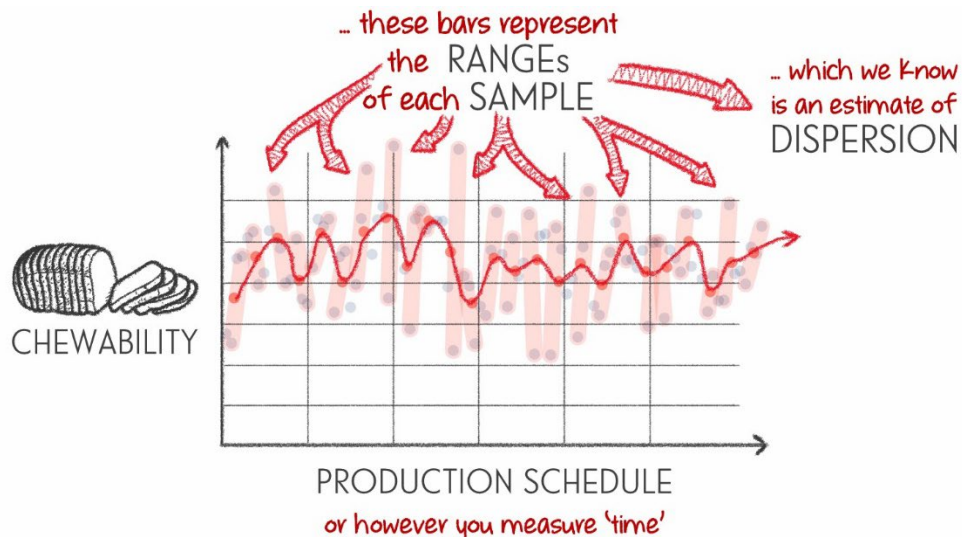


We can then find the **central tendencies** of each **sample** which will be indicative of the entire process' **central tendency** while still preserving a relationship with time (like production schedule).

The red line below represents the changing **central tendency** (of each **sample**) over time. This red line is smoother and effectively filters much of the variation out. The red points (**means** of each **sample**) has much less variation than the blue raw data points.

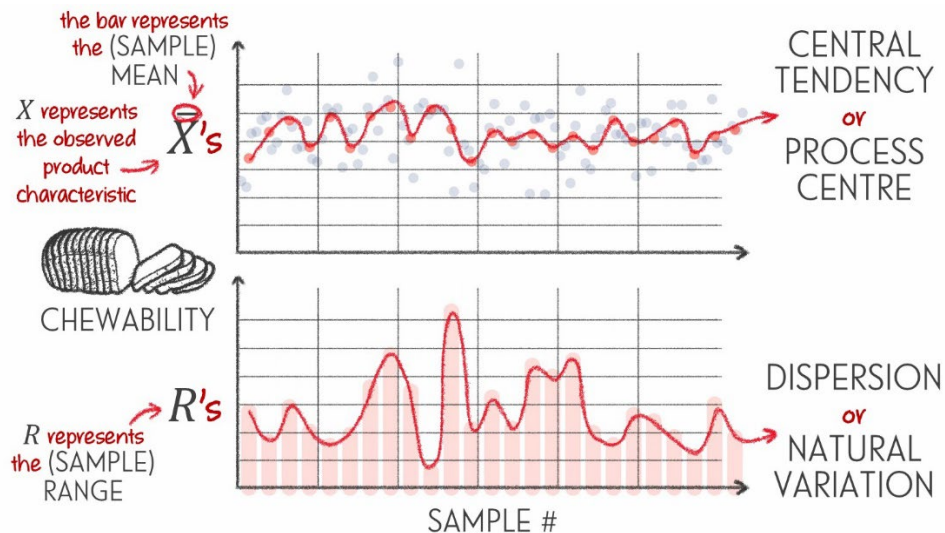


The next measure is **dispersion**. A very simple way of estimating **dispersion** for each sample is finding the **range** of each **sample**. The **range** is simply the difference between the highest and lowest **process** or **product characteristics** (**chewability**).



The chart above is not easily drawn like this! There are better ways of representing both **central tendency** (**sample means**) and **dispersion** (**sample ranges**).

The next step is to break our chart down into two separate charts. The first (top chart) illustrates an ESTIMATE of **central tendency** or the **process centre (signal)**. The second (bottom chart) illustrates an ESTIMATE of **dispersion** or **natural variation**.



The top chart is called an ' **\bar{X} - bar**' or ' **\bar{X} ' chart'. Placing a bar or a line over a variable is a common way of representing the **mean** of that variable. So ' **\bar{X} - bar**' is another way of saying 'the **mean** of \bar{X} .' In the chart above, \bar{X} represents the **mean** of each **sample** that contains four data points.**

The bottom chart is called an '**R' chart** where '**R**' represents **range**. By separating these two statistics out, we can more easily see how they evolve over time.

The \bar{X} - R chart above is based on an IN-CONTROL process whose process or product characteristic is NORMALLY DISTRIBUTED

Even **in-control processes** will have some ongoing **natural variation** or **noise**. The key now becomes working out when this ongoing variation suggests our process is **out-of-control**.

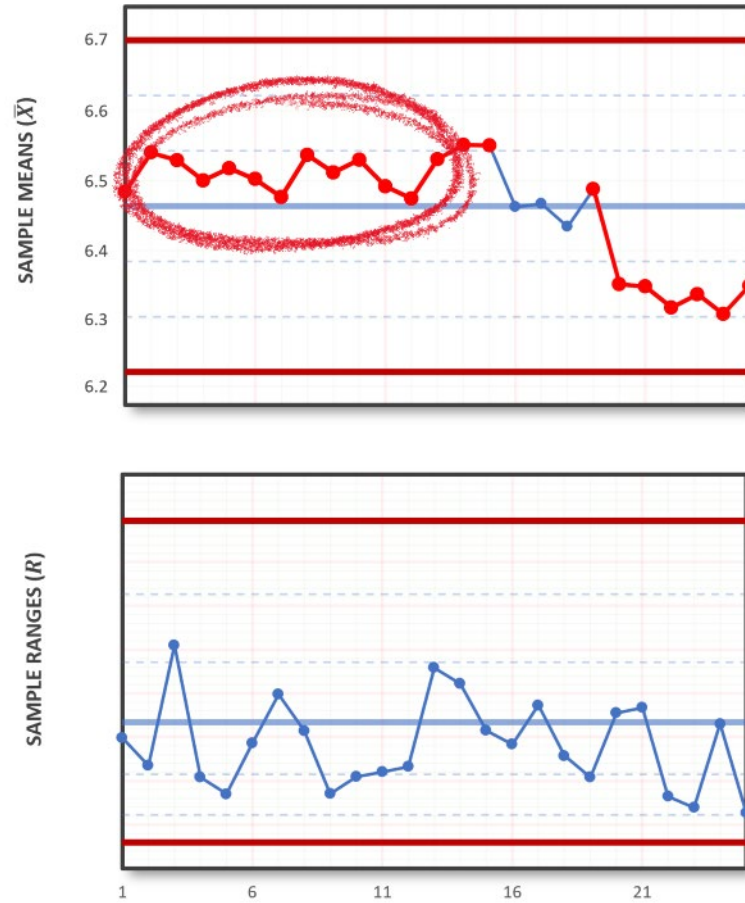
EXERCISE

Consider the following SPC data set.

SAMPLE #	OBSERVED CHEWABILITY DATA POINTS				
1	6.39	6.51	6.55	6.37	6.6
2	6.53	6.61	6.58	6.55	6.43
3	6.5	6.56	6.73	6.34	6.51
4	6.59	6.48	6.53	6.47	6.43
5	6.47	6.59	6.53	6.46	6.54
6	6.4	6.62	6.47	6.56	6.46
7	6.51	6.25	6.56	6.54	6.52
8	6.45	6.64	6.49	6.43	6.67
9	6.48	6.47	6.5	6.6	6.51
10	6.47	6.51	6.5	6.63	6.54
11	6.48	6.56	6.48	6.39	6.55
12	6.4	6.55	6.51	6.54	6.37
13	6.51	6.53	6.5	6.38	6.73
14	6.54	6.51	6.76	6.5	6.44
15	6.52	6.52	6.68	6.44	6.59
16	6.56	6.34	6.45	6.48	6.48
17	6.55	6.39	6.28	6.54	6.57
18	6.5	6.53	6.42	6.33	6.39
19	6.5	6.57	6.41	6.42	6.54
20	6.41	6.37	6.29	6.48	6.2
21	6.4	6.48	6.45	6.21	6.19
22	6.29	6.26	6.32	6.39	6.32
23	6.27	6.33	6.38	6.32	6.38
24	6.3	6.27	6.26	6.48	6.22
25	6.39	6.37	6.35	6.29	6.34

EXERCISE

Is the circled UNEXPECTED BEHAVIOUR below actually 'unexpected'?



What are some of the potential root causes for the 'issues' identified in the control charts above?

What is the next step?

Learning more about **SPC**. This was an introduction that focuses on WHY you should do **SPC**, 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.

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?