Module 10. Quality, Monitoring, Six Sigma, and Lean Manufacturing

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Quality control and process monitoring are essential topics in manufacturing and apply to any process. Quality control (QC) is concerned with detecting defects in products and taking corrective action to eliminate it. It is also concerned with statistical process control, Six Sigma, Lean Manufacturing, and inspection/monitoring technologies (such as CMM (coordinate Measuring Machine), Laser and Machine Vision, and other sensors and monitoring systems).

In any manufacturing process, variability such as dimensional differences exist from one part to the next. In order to establish and control quality, manufacturers must monitor and control process variation. All manufacturing processes have variation. For example, the wear of a tool and vibration can change the final size of a part, change in humidity and temperature of the environment can change the cooling time in injection molded or cast parts.

This module discusses basic statistical methods for monitoring and quantifying process control. Nowadays, in many industrial process quality checks must be done quickly; therefore sensors, optical inspection systems, or machines are built solely for the purpose of monitoring. Continuously obtaining data, using different sensors, to detect errors or predict a potential malfunction of a system before it becomes serious by searching the statistical data for patterns, using machine learning which is an application of AI (Artificial Intelligence) is one of the hot topics in manufacturing.

This Module objective:

- An example of monitoring process in Gear production. (It will be covered during class lecture; a separate lecture note is posted on Canvas)
- Use normal distribution statistics to quantify variation from a manufacturing process.
- Understand the basics of statistical process control and design capability index in manufacturing operations.
- Basic familiarity to concepts such as Six Sigma, Kaizen and Lean Manufacturing

Basic termonogies in statistical process control:

Quality: The ability of a product to consistently meet customer needs.

Variation: A change in outcome of a process

Tolerance: Allowable limit of variation of a process

Quality from the point of view of the customer can be subjective. And even with a design properly suited to meet the customer's needs, manufacturers must translate the customer's perception of quality into measurable metrics of the outcome of their process. A manufacturer must know:

- What the customers want (expectation) and how to relate it to a product specification?
- How to quantify variation?
- What causes variation?
- How to minimize variation?
- How to monitor variation?

Bolt Diameter Example:

Let’s assume we produced 100 bolts and we measured the bolt diameter. There are different possible methods to conduct the measurement (figure below). Let’s say, we picked the most accurate available method (caliper).

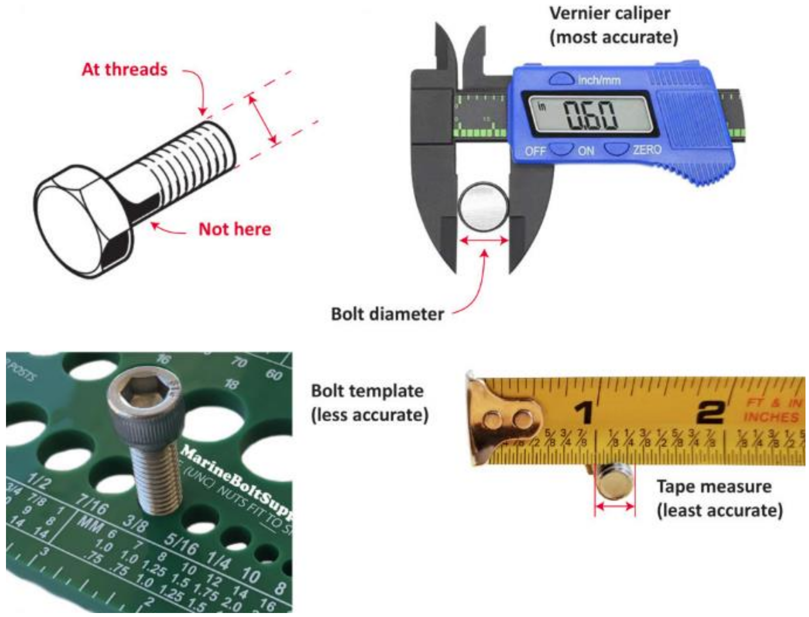
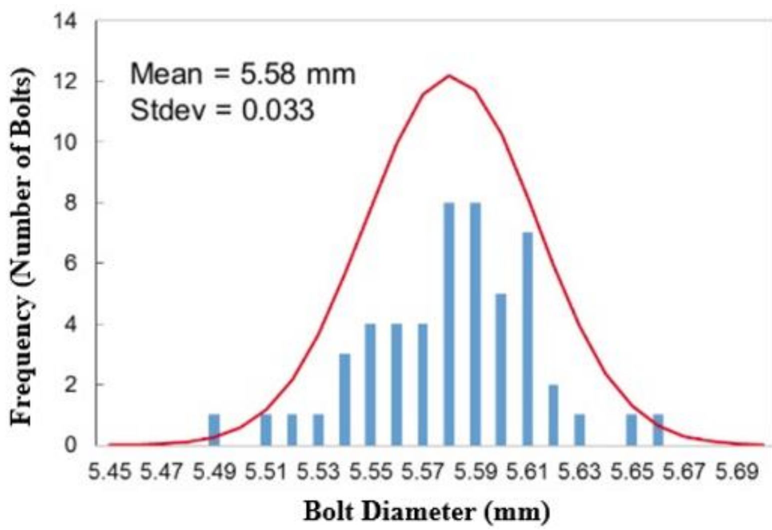


Image source: https://ricksfreeautorepairadvice.com/how-to-measure-a-bolt/

Then, we plot the histogram of the data (the bolt diameter). Here is a plot of number of observations (frequency) of bolts dimeter. This graph shows the distribution of data. The results show the mean value of the bolt diameter is $5.58mm$ and the standard deviation is 0.033. But, what is the meaning of variation we measured?



Normal Distribution:

The Normal distribution was developed by Gauss in 1801. His procedure was based on three assumptions:

1. Small errors are more likely than large errors.
2. Positive and negative errors are equally likely.
3. The most likely of several measurements is their average.

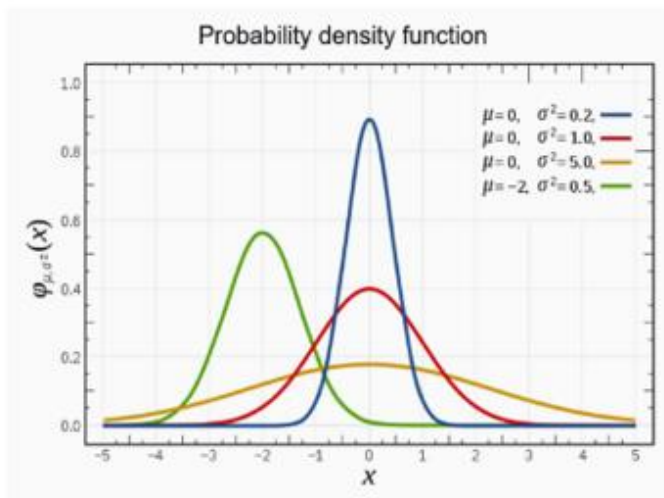
$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}}\, e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

$$\boldsymbol{\sigma} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})}$$

μ = mean

σ = standard deviation

σ² = variance



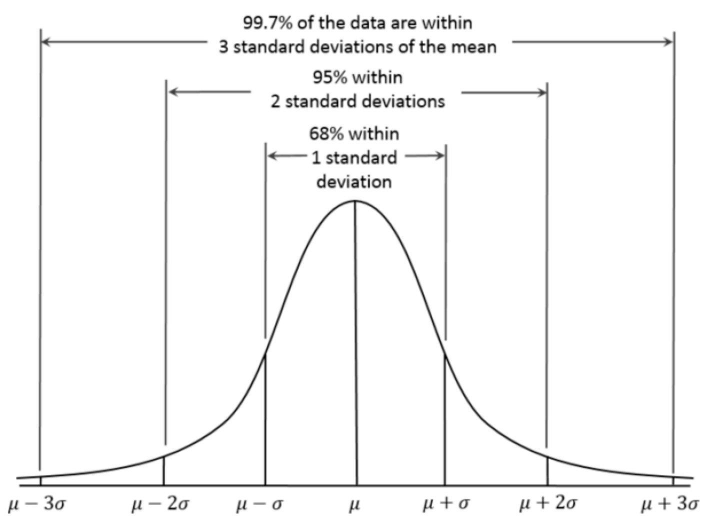
Wikipedia

Standard Normal Distribution:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}}\, e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

For “standard” curve

μ = 0 and σ = 1



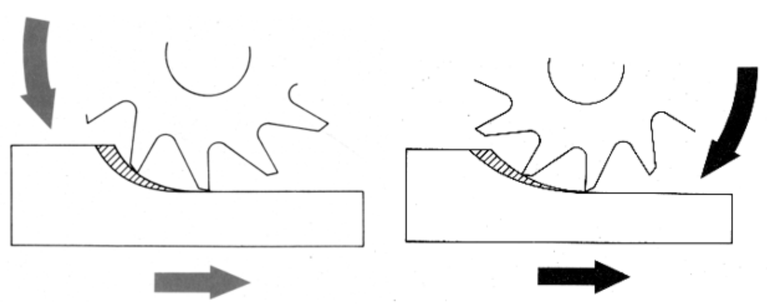
Wikipedia

In general, all measurements and measured objects have some amount of variability. Mean gives the most likely estimate of the actual quantity that is measured. Standard deviation describes the variation in the measured quantity. The Normal Distribution is a good general method to visually see the distribution of data.

What can cause variation in a manufacturing process?

- **The process:** change of setting
- **Material:** raw material variation, defects
- **Equipment:** tool wear, maintenance, calibration, vibration
- **Operator:** distraction, new operator with less skill, tiredness
- **Environment:** Humidity, temperature
- **Measurement:** capability of measurement tool

For example, if you change the setup from climb cutting to counter cutting, the resultant forces on the tool increases, as a result the tool deflect more, and the output size will be bigger.

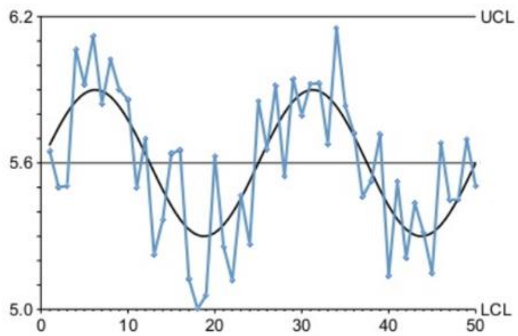


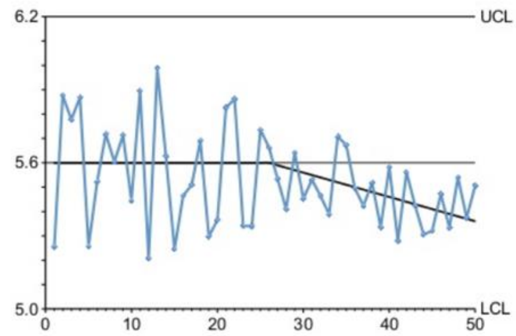
Climb cutting
(Direction of cutter rotation
same as feed direction)

Counter cutting
(Direction of cutter rotation)
oppose to feed direction

Also, you studied in module#1 that the machine, tool, and workpiece are flexible and will deflect during the machining. There is also heat generation during machining. All of these may affect the output.

Example) Assume we are producing shafts with diameter of $5.5mm$ by machining. The plots below show the diameter of each shaft for 50 samples in the morning and 50 samples produced in the afternoon during a day of manufacturing. What might have been gone wrong in each case? (explain the low and high frequency fluctuations)





…. *in class discussion*….

Control Charts:

In order to conduct statistical analysis of a manufacturing process, the frequency of sampling for measurement (number of parts to be measured during production) must be defined. It depends on - Cost of measurement, -Importance of defects, -Likelihood of unexpected disturbance, -Experience. Also, the lower and upper control limits (LCL, UCL) for each output must be defined. These numbers are usually based on exitance statistics of sample variation.

A ***control chart*** is a graphical technique in which statistics computed from measured values of a certain process or part (for example the dimension of a part or bending strength of a part) are plotted over time to determine if the process remains in statistical control. The chart consists of 3 horizontal lines, Lower Control Limit (LCL), Upper Control Limit (UCL), and a Center.

Assume there are N parts manufactured. Control charts are constructed based on the measurement of samples (n samples). There are two types of control charts:

- **Average chart** (plot of mean value of samples, centered around the mean of all samples)
- **Range chart** (plot of range of n sample, centered around the average range)

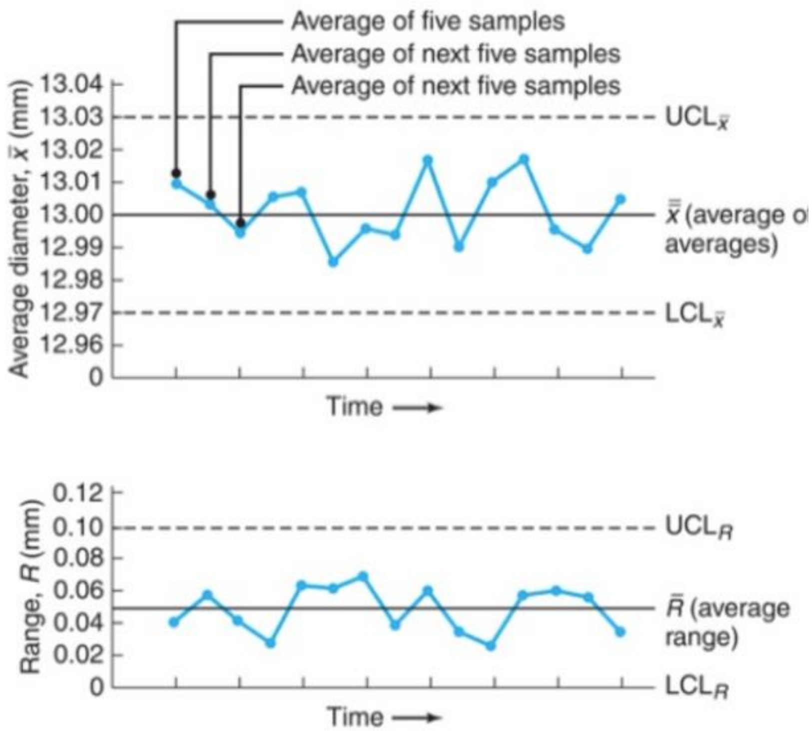
The following graphs illustrate an average chart and a range chart. The LCL, and UCL can be computed using the average of averages, the average range, and the constant A_2.

$$\overline{\overline{X}} = \frac{\sum_{i=1}^{N} \overline{X}_i}{N}$$

$$\overline{R} = \frac{\sum_{i=1}^{N} R_i}{N}$$

$$LCL = \overline{\overline{X}} - A_2 \overline{R}$$

$$UCL = \overline{\overline{X}} + A_2 \overline{R}$$



The constant A2 can be computed from the following table (for a 3-Sigma approach):

n (sample size)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
A_2 (Constant)	1.8	1.02	0.72	0.57	0.48	0.47	0.41	0.33	0.30	0.28	0.26	0.24	0.23	0.22	0.21	0.20	0.19	0.18	0.17	0.16

The value of A_2 for other standard deviations are tabulated and available on internet.

Extra materials to read (optional): Interested to know where A_2 comes from, you can read from this link: https://andrewmilivojevich.com/control-chart-constants-how-to-derive-a2-and-e2/

Tolerance and Process Capability Index:

The issue of tolerance is critical to product quality; but keep in mind that, as the tolerance is reduced, the cost of product increases. Also design tolerance must be compatible with ***process***

capability. For example, to specify a tolerance of $\pm 0.01mm$ on a dimension if the process is only capable to produce parts with dimensional accuracy of $\pm 0.25\ mm$.

The upper and lower boundaries of tolerance are known as the tolerance limits. These numbers are set based on the allowable variability that will achieve required function and performance. The ration of the tolerance range to the natural tolerance limit (6σ) is known as the process capability index. In other words, by definition, process capability equals ±3 standard deviations about the mean value (a total of 6 standard deviation).

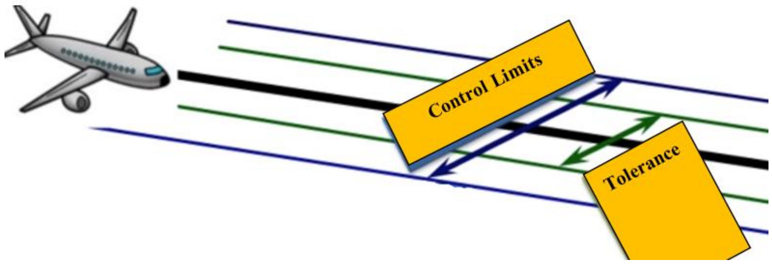
$Process\ Capability = \mu \pm 3\sigma$

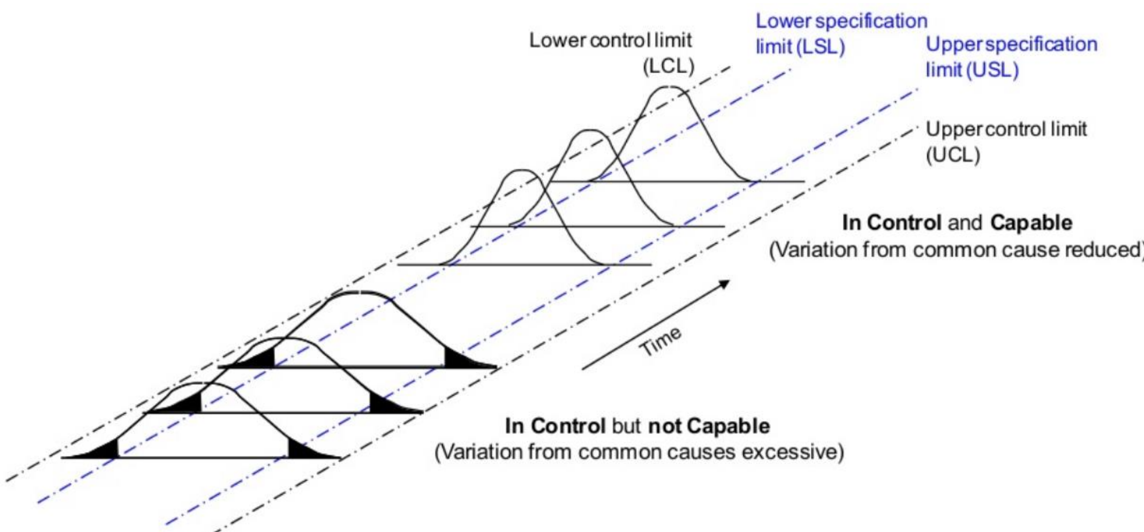
The process capability of a manufacturing operation is not always known, and experiments must be conducted to estimate the natural tolerance limits and the process capability.

The following table summarizes the defect rate when tolerance is defined in terms of number of standard deviations of the process.

No. of Standard Deviation	C_p	Defective Parts/1000000
± 1	0.333	317400
± 2	0.667	45600
± 3	1.33	63
± 4	1.5	8
± 5	1.667	6
± 6	2	3.4

Control limits are characteristic of the process and measurement method. They are based on the process mean and variability, and dependent on the sampling parameters. While tolerance are the limits we specify and are used to establish comfortability of a part to the design intent. Also, we need to consider the capability of a process; in other words, even if a process is in control, it may not be capable to give us what we want as set by the tolerances/specifications. As an analogy, consider the landing strip for a pilot. Let's say the landing width is set (control limits), which every pilot must land with this limit. Then, one airline expects its pilots to land with a smaller width (tolerance or specification of this airline). Let's assume, the pilots have all the skills to land with the tolerance limit, but the planes are old and are not capable to perform landing in a narrow landing strip. Here we say, the process (landing) is in control limit, but not capable to meet the specification.





A systematic way to quantify and compare a process control and capability is to define ***process control index***.

A process capability is defined by:

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

Setting C_p is not an easy task; mainly because it depends on judging what is good enough! Also, it depends on the knowledge of the "cost of defects" in our product.

As a rule of thumb, C_p should be at least 1.33 which means 63 defect parts in 1000000 production. The table below shows the recommended values for process capability.

	Recommended C_p	Defects (out of spec)/1000000
Existing process	1.33	63
New process	1.5	8
Parts which safety is critical	1.67	6
Absolute Quality	2	3.4

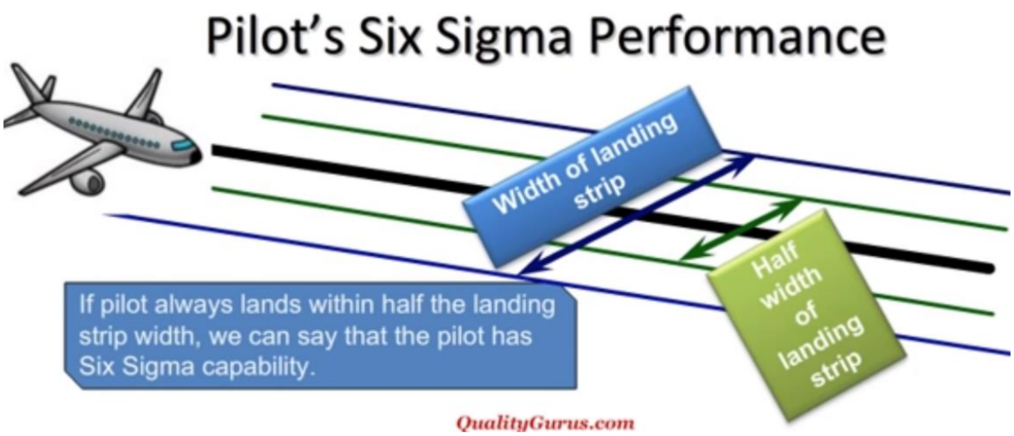
Use the following links to study the design capability and the principles of statistical process control with more details:

- Process Capability Index Part 1
- Process Capability Index Part 2
- Process Capability Index Part 3

A Brief Introduction to Six-Sigma:

A traditional measure for good process quality is three Sigma level ($\pm 3\sigma$). It assumes that the process is stable and in statistical control, and the variable representing the output of the process is normally distributed. Based on these conditions, 63 parts per 1000000 will be outside the specifications.

The desire to achieve very low number of defective parts has led to the notion of "Six Sigma". Achieving Six-Sigma limits virtually eliminates defects in products, assuming the process is maintained within statistical control.



The purpose of six sigma quality program is to make customer happier and increase profits. It is done by reducing variation and defects. It was first introduced and used by Motorola Corporation in 1986. It is a philosophy of improvement. Based on the six-sigma philosophy:

- Anything less than ideal is an opportunity for improvement.
- Defects costs money
- Reduce variation
- Identify the root causes of performance deficiencies

Six Sigma approach:

Six sigma establishes measurable targets for quality based on the number of standard deviations (sigma σ) away from the mean in the normal distribution. A process operating with Six-sigma quality produces less than 3.4 defects per 1000000 parts.

DMAIC approach is used to achieve Six-Sigma performance. The steps are:

- **Define** the problem
- **Measure** the defect
- **Analyze** the data
- **Improve** the process to eliminate the defect
- **Control** and sustain the improvement

Based on the Six sigma approach, the defects in any process must be measured and quantified. Then the cause of the defects must be identified, and improvements can be made to eliminate or reduce the defects.

Advantages of Six-Sigma:

- Customer driven
- Looks at entire process
- Proactive to improve defect

Disadvantages of Six-Sigma:

- Complex administrative process
- Expensive

A Brief Introduction to Kaizen methodology:

改善

KAIZEN is a Japanese word for "Change for the better" or it is also referred to as "Continuous Improvement". It uses personal creativity and ingenuity to identify problems and then develop and implement ideas to solve those problems. KAIZEN philosophy says that everything can be improved, and everything can perform better or more efficiently.

KAIZEN is the practice of continuous improvement. KAIZEN was originally introduced to the West by Masaaki Imai in his book KAIZEN: The Key to Japan's Competitive Success in 1986. Today KAIZEN is recognized worldwide as an important pillar of an organization's long-term competitive strategy. The KAIZEN principles are:

- Good processes bring good results
- Go see for yourself to grasp the current situation
- Speak with data, manage by facts
- Take action to contain and correct root causes of problems
- Work as a team
- KAIZEN is everybody's business
- Big results come from many small changes accumulated over time

A Brief Introduction to Lean Manufacturing:

History: ***Lean thinking*** and later ***Lean manufacturing*** strategy was invented by Toyota, known as T.P.S. (Toyota Production System) based on these principles:

- Only make what we need, when we need it.
- Remove waste (in production)
- Respect employee

Due to global competition, there is a need to change; because:

- someone will design and make a better quality part for less
- customers want more (better quality, faster delivery, lower cost)

Lean is an operational excellence strategy that enables a manufacturer to change for the better. It is based on the following philosophies:

- Slow but consistent (slow and steady wins the race)
- Small improvements (How can we improve something today?)
- Never settle for good (focus on finding a better way)
- Persistence pursuit in elimination of waste
- Eliminate any activity that adds no real value to the product.
- Respect for people/employee
- Improve the quality and the stability of a process
- Go and see what is happening at the place the work is done (if there is a problem at the production floor, the management team shouldn't attempt to solve it from boardroom!)
- Fail better (willing to try and fail from time to time)

Lean strategy is applicable in other environments as well; for example, in offices reduce the time to process customer orders, in health care remove errors, and many other industries such as military, post services, supermarkets, and so on.

Lean Tools (Methodologies):

Lean is the set of "tools" that identifies and eliminate waste. As waste is eliminated quality improves while production time and cost are reduced. A non exhaustive list of such tools would include: SMED (Single-minute exchange of die), value stream mapping, 5S, Kanban (pull systems), poka-yoke (error-proofing), TPM (Total Productive Maintenance), elimination of time batching, mixed model processing, rank order clustering, single point scheduling, redesigning working cells, multi-process handling and control charts, Cellular manufacturing, Andon lamps, A3 thinking, 3P, Water Spider, and many other tools. Some of these tools are briefly explained below:

1- **5S** (Sort, Straighten, Shine, Standardize, Sustain)

The purpose of 5S is to identify abnormalities in a production line.

2- Value Stream Mapping

The purpose is to realize the detect waste

3- Cellular Manufacturing

- Quick flow with now delay
- an individual process does not start until the down stream tells it to. It is known as One-piece flow. For this, all machines must run smoothly, therefore machine breakdowns must be avoided.

4- Andon Lamps

Image source: https://www.indiamart.com/proddetail/andon-14838292548.html

Like the "check engine" light in a car, Andon in Lean manufacturing is a system designed to alert operators and managers of problems in real time so that corrective measures can be taken immediately. It originates from the Toyota Production System (TPS) which empowered operators to recognize issues and take the initiative to stop work without waiting for management to make the decision. Andon can take many forms. It can be activated by an operator pulling a cord or pushing a button or it can be automatically activated by equipment when a problem is detected. Whether it is because of part shortage, equipment malfunction, or a safety concern, the point of Andon in Lean manufacturing is to stop work so that the team can gather and perform a real-time root cause analysis and quickly apply a solution. Once the problem is resolved and work continues, the occurrence is logged as part of a continuous improvement system.

Read more: https://leankit.com/learn/lean/what-is-andon-in-lean-manufacturing/

5- **A3 thinking**

A3 problem solving is a structured problem-solving and continuous-improvement approach, first employed by Toyota and typically used by lean manufacturing practitioners. It provides a simple and strict procedure that guides problem solving by workers. The approach typically uses a single sheet of ISO A3-size paper, which is the source of its name.

Read more:

https://citoolkit.com/templates/a3-template/#:~:targetText=A3%20Thinking%20is%20a%20logical,Lean%20organizations%20around%20the%20world.&targetText=The%20A3%20Template%20provides%20a,the%20standard%20A3%2Dsize%20papers.

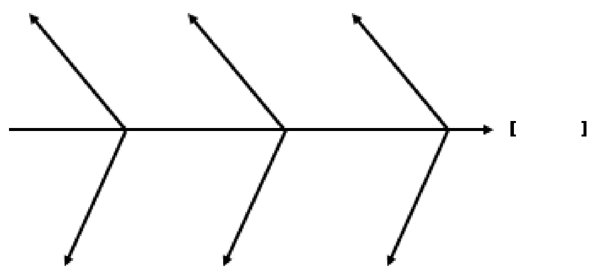
Here is one example of A3 template:

A3 Problem Solving

Title	Start Date	Estimated Completion Date

Problem Description	Problem Category	
	Quality	Waste and efficiency
	Cost	Health and safety
	Delivery	Customer satisfaction
	Moral	Other

Goal	Expected Benefits

Cause and Effect and 5 Whys	Cause Analysis Summary (Prioritize in order of importance)
	

Corrective Actions and Quick Wins	Team members	
Priority	**Name**	**Role**

Implementation Plan

Activity	Who?	Start Date	Due To	Status

Result Summary (Including benefits obtained)	Follow-up Actions			
	What?	**Who?**	**When?**	**Status**

6- 3P

Lean 3P (Production Preparation Process) is an event-driven process for developing a new product. Lean 3P brings stakeholders together and sequentially takes them through a process where products are developed alongside of the manufacturing operations.

7- Visual Controls

The status of practically every process should be visible in lean management. Visual controls and the processes surrounding them represent the nervous system in lean management. Visual controls bring focus to the process and drive improvements.

8- Water Spider

Water Spider is a lean manufacturing term referring to a person in a warehouse or production environment who is tasked with keeping workstations fully stocked with materials, thus controlling the continuous flow of productivity.

Read more: https://www.velaction.com/water-spider-mizusumashi/

Watch a summary of Kaizen methodology v.s. Six-Sigma from this video:

What is the difference between Kaizen methodology, Lean Manufacturing, and Six-Sigma? Read from this link:

https://in.kaizen.com/blog/post/2015/09/11/what-is-the-difference-between-kaizen-lean--six-sigma.html