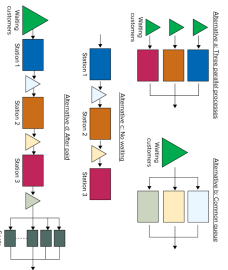


Process Analysis and Improvement

Process Flow Diagram and Little's Law

Process Flow Diagram



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Little's Law

$$\text{Inventory} = \text{Flow rate} \times \text{Flow time}$$

$$I = R \times T$$

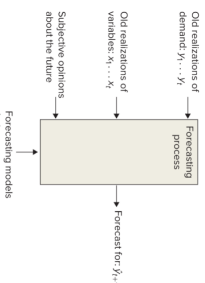
$$\text{Inventory} = I$$

$$\text{Flow Rate} = R$$

$$\text{Flow Time} = T$$

Forecasting

Forecasting



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$$\text{MSE} = \frac{\sum_{t=1}^N \text{FE}_t^2}{N}$$

$$\text{MAE} = \frac{\sum_{t=1}^N |\text{FE}_t|}{N}$$

$$\text{MAPE} = \frac{\sum_{t=1}^N \frac{|\text{FE}_t|}{y_t}}{N}$$

Introduction to Operations Management

Strategic Trade-offs, Efficient Frontier, Inhibitors

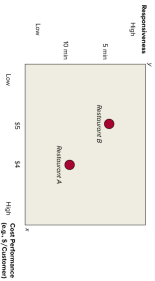


Figure 1.1 The strategic trade-offs between responsiveness and profitability

- **Waste** – The consumption of inputs and resources that do not add value to the customer.
- **Variability** – Predictable or unpredictable changes in the demand of the supply process.
- **Flexibility** – The ability of the supply process to adapt changes in the supply process or changes in customer demand.

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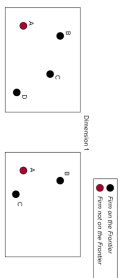


Figure 1.2 The position of the efficient frontier

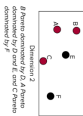


Figure 1.3 The position of the efficient frontier

Process Analysis and Improvement

Process Improvement

Costs of direct labor = $\frac{\text{Wages per unit of time}}{\text{Flow rate}}$

Labor content = Sum of the processing times involving labor

Average labor utilization = $\frac{\text{Cycle time} \times \text{Number of employees}}{\text{Labor Content}}$

Total idle time = Cycle Time $\times$ Number of employees – Labor Content

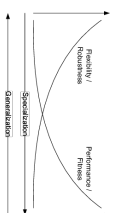
Takt time = $\frac{\text{Demand rate}}{\text{Labor content}}$

Target takttime = $\frac{\text{Labor content}}{\text{Takt time}}$

Strategies to improve:

- Off-load the bottleneck
- Balance the line

Pros and Cons of Specialization



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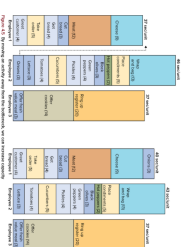
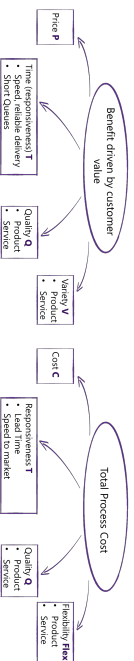


Figure 1.5 The trade-off between specialization and flexibility

Introduction to Operations Management

Firms compete on delivered value

$$\text{Delivered value of a process} = \text{benefit driven by customer value} - \text{total process cost}$$



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Process Analysis and Improvement

Process Analysis and Bottlenecks



Capacity = $\frac{m}{\text{Processing time}}$

Flow rate = Minimum (Demand, Process capacity)

Utilization = $\frac{\text{Flow rate}}{\text{Capacity}}$

Cycle time = $\frac{1}{\text{Flow rate}}$

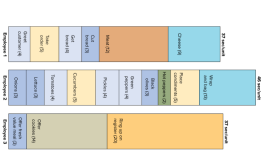
Time to finish X units = $\frac{\text{Time through an empty system}}{\text{an empty process}} + [(X - 1) \times \text{Cycle time}]$

Bottleneck – Resource with the lowest capacity in a process. Understanding the location of the bottleneck is critical for improving a process.

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Inventory Management Newsvendor Model

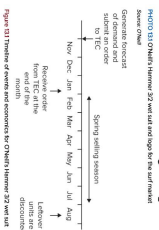
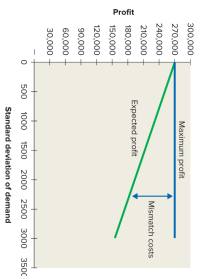


Figure 13.1 Timeline of events and decisions for O'Neill's Hurdles 32 wet suit

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$$F(Q^*) = \frac{C_u}{C_o + C_u}$$

Time to Serve Customers

- Time to serve the person arriving at time $T = T \times \left(\frac{\text{Demand}}{\text{Capacity}} - 1 \right)$
- Time to serve the Q_{th} person in the queue = $\frac{Q}{\text{Capacity}}$

Question: During the three hours of the morning rush from 6 a.m. to 9 a.m., 10,000 cars per hour arrive at the toll plaza of a bridge. However, only 8,000 cars can be processed per hour. How long does the car arriving at 9 a.m. have to wait to get through the toll plaza?

Answer: The car arriving at 9 a.m. arrives three hours from the time the queue starts to build. So,

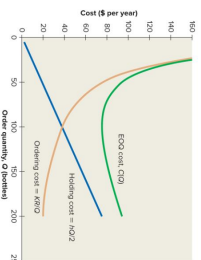
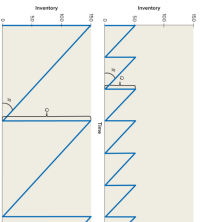
$$\begin{aligned} \text{Time to serve the car arriving at 9 a.m.} &= 3 \text{ hours} \times \left(\frac{10,000 \text{ cars per hour} - 1}{8000 \text{ cars per hour}} \right) \\ &= 0.75 \text{ hour} \end{aligned}$$

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Inventory Management EOQ Model – constant demand with non-perishable inventory



$$\text{EOQ cost per unit of time} = C(Q) = \left(K \times \frac{R}{Q} \right) + \left(\frac{1}{2} \times h \times Q \right)$$

$$Q^* = \sqrt{\frac{2 \times K \times R}{h}}$$

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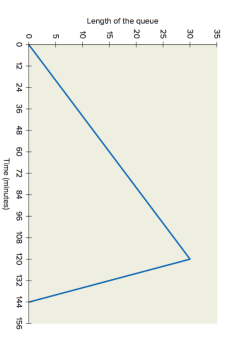
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Length of the Queue

Queue growth rate = Demand – Capacity

Length of queue at time $T = T \times \text{Queue growth rate}$
 $= T \times (\text{Demand} - \text{Capacity})$

Time to serve the Q_{th} person in the queue = $\frac{Q}{\text{Capacity}}$

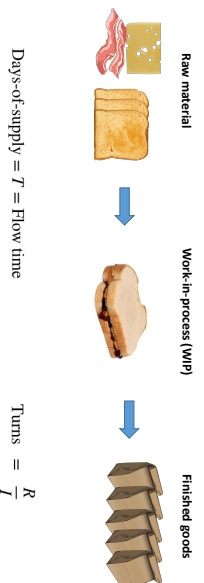


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Inventory Management Introduction to Inventory

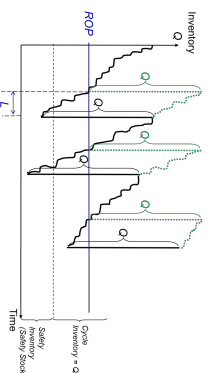


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Inventory Management ROP for Frequent Orders



$$\begin{aligned} \text{Safety stock} &= Z^* \sigma \sqrt{L} \\ \text{ROP} &= D^* L + Z^* \sigma \sqrt{L} \end{aligned}$$

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The Arrival and Service Processes

- **Arrival process** – the flow of customers arriving to the system.
- **Service process** – the flow of customers when they are being served.
- **Interarrival time** – the time between customers arrivals to a system.
- **Processing time** – the time a customer spends with a server.

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Predicting Time in Queue, T_q ; Time in Service; and Total Time in the System

Given the queuing model in previous slide, the average time a customer waits in the queue is:

$$T_q = p \times \left(\frac{\text{Utilization}}{1 - \text{Utilization}} \right) \times \left(\frac{CV_d^2 + CV_p^2}{2} \right)$$

Let's use the above equation to estimate the average wait for customers at the An-ser call center in the hour between 1 a.m. and 2 a.m.:

$$T_q = 4 \text{ minutes} \times \left(\frac{0.8}{1 - 0.8} \right) \times \left(\frac{1^2 + 1^2}{2} \right) = 16 \text{ minutes}$$

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Managing Peak Demand: Capacity

Adjusting Capacity?

- **Pre-processing strategy** – reducing the amount of work needed to process a customer during the peak time period by moving some of the work to an off-peak time.

If each customer requires less work during the peak time, the person's capacity to serve customers during that time is increased.

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A Queuing Model with a Single Server

- **Queuing model** – an abstract representation of the queue that enables us to predict waiting times and other performance measures.
- Many different models
 - In the An-ser example:
 - There is one server.
 - There is a single queue.
 - Once a customer arrives to the system, the customer waits until service is completed.
- p = The server's processing time.
- a = The average interarrival time of customers.
- CT_d and CT_p are the coefficients of variation of the interarrival times and the processing times, respectively.
- The average interarrival time is greater than the average processing time; $p < a$.

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Average Waiting Time

$$\text{Average time to serve a unit} = \frac{1}{2} \times T \times \left(\frac{\text{Demand}}{\text{Capacity}} - 1 \right)$$

- Two factors that determine average wait:

1. Ratio of demand to capacity: Demand/Capacity
2. Duration of the busy period

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Variation in the Arrival and Service Processes

a = Average interarrival time

p = Average processing time

- **Coefficient of variation** – the ratio of the standard deviation to the average.

In general, the coefficient of variation of the arrival process is defined as

$$CV_a = \frac{\text{Standard deviation of arrival process}}{a}$$

and the coefficient of variation of the service process is defined as

$$CV_p = \frac{\text{Standard deviation of service process}}{p}$$

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Utilization, the Number of Servers, and Stable Queues

- Using the An-ser example:

- The capacity of each server is $1/p$. The capacity of the call center with m servers is m times the capacity of a single server, or m/p . Hence, the utilization of the servers is:

$$\text{Utilization} = \frac{\text{Flow rate}}{\text{Capacity}} = \frac{1/a}{m/p} = \frac{p}{a \times m}$$

- If An-ser has six agents, then their utilization is:

$$\text{Utilization} = \frac{p}{a \times m} = \frac{120}{25 \times 6} = 0.80$$

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Predicting Waiting Time in Queue, T_q

The equation for the average waiting time in queue is similar to the analogous equation in the queuing model with a single server:

$$T_q = \left(\frac{p}{m}\right) \times \left(\frac{\text{Utilization} \sqrt{2(m+1)} - 1}{1 - \text{Utilization}}\right) \times \left(\frac{CV_a^2 + CV_p^2}{2}\right)$$

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Predicting the Number of Customers Waiting and in Service

I_q is the average number of customers waiting and I_p is the average number of customers in service. As these are “inventories,” we can apply Little’s Law to evaluate them:

$$I_q = R \times T_q = \frac{T_q}{a}$$

$$I_p = R \times p = \frac{p}{a}$$

If the time waiting in the queue, T_q , increases, then the number of people in the queue increases as well. The average number of people in service, I_p , is the same as the utilization of the server: if the server is busy 80 percent of the time, then 80 percent of the time there is one person in service!

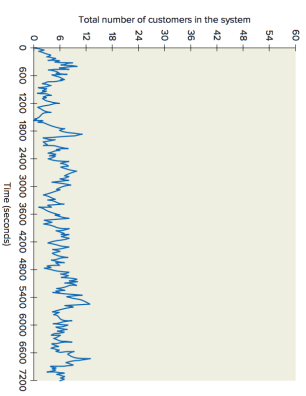
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Stable Queue

Stable queue – a queuing system in which the demand rate is less than capacity.



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The Key Drivers of Waiting Time

- Processing time** – capacity factor of the server.
 - p is the processing time
- Utilization Factor**

$$\frac{\text{Utilization}}{1 - \text{Utilization}}$$
- Variability Factor**

$$\frac{CV_a^2 + CV_p^2}{2}$$

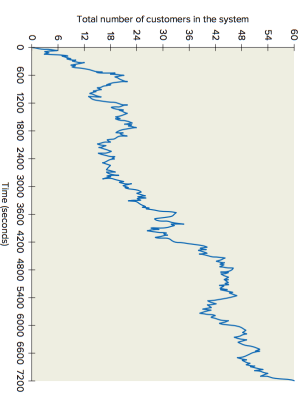
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Unstable Queue

Unstable queue – a queuing system in which the demand rate exceeds capacity.



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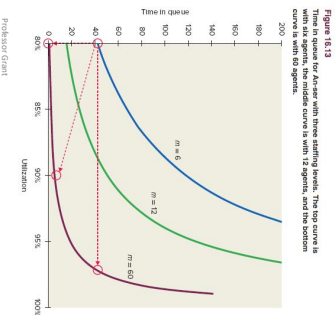
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The Power of Pooling

Economies of scale – As the number of servers increases, the system is more resilient to high utilization (wait time is less sensitive to high utilization)

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What is Wasted Time?



- **Waste of time at a resource** – the waste of time from the perspective of a resource, which reduces the capacity of the resource.
- **Waste of time of a flow unit** – the waste of time from the perspective of a flow unit, which makes the flow time of that flow unit longer than what is needed from the customer's perspective.

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Queuing System Design—Economies of Scale and Pooling

Three key drivers of time in queue of the multiple-server:

1. Capacity factor: $\left(\frac{p}{m}\right)$
2. The Utilization factor: $\left(\frac{\text{Utilization} \sqrt{2(m+1)} - 1}{1 - \text{Utilization}}\right)$
3. The Variability factor: $\left(\frac{CV_a^2 + CV_p^2}{2}\right)$

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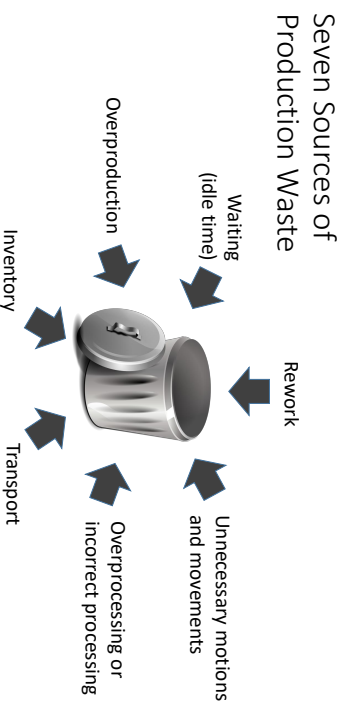
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Predicting Average Number in System

Use Little's Law to evaluate the average number of waiting customers:

$$I_q = R \times T_q = \frac{T_q}{a}$$

and the number of customers in service:

$$I_p = R \times p = \frac{p}{a}$$

These formulas are identical to the ones used for the single-server queue.

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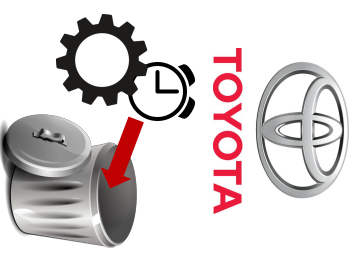
What is Lean Operations?

- **Toyota Production System (TPS)** – a framework used to run operations with the goal of reducing both the waste of capacity (resources) and the waste of flow time (flow units), thereby making sure supply and demand are matched *just in time*.
- **Lean Operations:** the term 'Lean' coined by James Womack, it reflects TPS's goal to eliminate the waste from the system.

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Value-added percentage

The percentage of flow time used for value-added work.

Value-added percentage = $\frac{\text{Value-added time of a flow unit}}{\text{Flow time}}$

Note: The measure focuses on time of a flow unit (flow time) whereas OEE focuses on resource time.
$$\text{OEE} = \frac{\text{Value-added time (of resource)}}{\text{Total available time}}$$

TPS Pillar 1: Single-Unit Flow & Just-in-Time Production

Key flow concept: smooth and continuous flow that matches supply with demand – the process produces the right materials in the right amounts at the right time (Just-in-time).

- **Run like the tortoise, not the hare** – an ancient fable used by Ohno to illustrate that a **steady and even pace** (the tortoise) wins over a pace that is uneven across time (the hare)
- **Single-unit flow** – operate at a flow of one unit at a time from one resource to the next instead of operating based on transfer batches. **That is, no batching is allowed.** While batching may save the setup times but moves supply out of sync with demand.
- By smooth and even flow, create balance (with no idle time) and match supply with demand



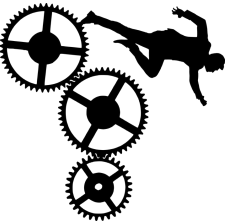
OEE

Overall Equipment Effectiveness (OEE) – the percentage of total available time that is used in a way that adds value to the customer.

$$\text{OEE} = \frac{\text{Value-added time}}{\text{Total available time}} = \frac{\text{Unplanned time} + \text{WASTE} + \text{Non-value-added time} + \text{Value-added time}}{\text{Total available time}}$$

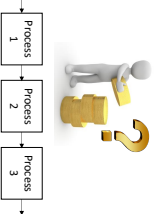
Improvement Methods

- **Kaizen** – the process of making small changes to the process with the goal of eliminating waste.
- **Just-in-time (JIT) Production** – supplying a unit of demand when and where it is needed, thus avoiding unnecessary inventory.



Wasting time of a resource:
What are the types of work?

- **Non-value-added work** – does **not** add value in the eyes of the customer, but must be done under the current conditions of the process in order to complete a unit.
- **Value-added work** – operations valued by the customer because they are required to transform the flow unit from its inputs to being the output the customer wants.



The Architecture of the Toyota Production System: 4Ps

Philosophy	Processes	People	Problem solving
 A long-term approach that favors quality and capabilities over short-term financial goals	 Continuous process flows that match supply with demand, aiming to reduce waste of flow time and capacity	 Respectful interactions with employees and partners emphasizing skill development and growth	 Ongoing improvement of the operations leveraging the experience of the front-line employees

Computing Takt time & Determine a Level Production Schedule

The rate of process flow ought to be dictated by demand. The demand time is translated to a takt time, setting the rhythm for the process.

$$\text{Takt time} = \frac{\text{Available time}}{\text{Demand rate}}$$

$$\text{Target manpower} = \frac{\text{Labor content}}{\text{Takt time}}$$

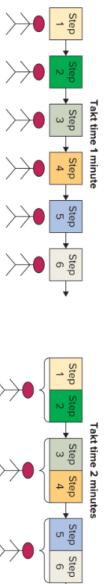


Figure 8.7 The impact of takt time on staffing requirements (Note: The figure assumes a 1 minute/unit activity time at each station.)

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Andon example:

Andon – a system consisting of a visible board and a cord running adjacent to the assembly line. Any employee detecting a problem can pull the cord to stop the line.



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Pull system

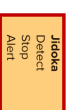
- **Pull system** – the resource furthest downstream (closest to the market) is paced by market demand. In addition to its own production, it also relays the demand information to the next station upstream, thus ensuring that the upstream resource also is paced by demand. It is an operating system in which the production of a unit is only initiated when a demand occurs.
- To implement a pull system, **two forms of process control**:
 - **Kanban** – production and inventory control system in which production instructions and parts delivery instructions are triggered by consumption of parts downstream.
 - **Make-to-order** – the release of work into a system only when a customer order has been received for that unit.

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TPS Pillar 2: Expose Problems & Solve Them When They Occur



- **Jidoka**: Upon detection of a problem, shutting down the machine to force a human intervention, which in turn triggers process improvement.
- **Detect-stop-alert** – the philosophy of halting production when a quality problem is discovered.
- **Andon** – a system consisting of a visible board and a cord running adjacent to the assembly line. Any employee detecting a problem can pull the cord to stop the line.
- **Information turnaround time (ITAT)** – the time between creating a defect and receiving the feedback about the defect.

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TPS Pillar 1: Single-Unit Flow & Just-in-Time Production

Achieving smooth single-unit flow requires some changes in the process.

- Implementing a pull system
- Transferring units piece by piece (no transport batching)
- Operating on takt time
- Leveling the demand rate so that the takt time does not constantly change and providing the flexibility in the process to produce different variants of a product.

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TPS Pillar 2: Expose Problems & Solve Them When They Occur

Process circles to address quality problems

1. Detect Quality Problems
2. Analyze Root Cause
3. Avoid recurrence

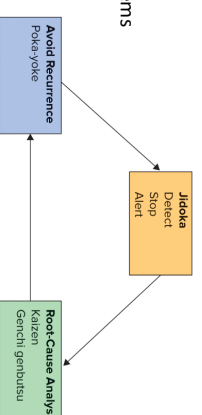
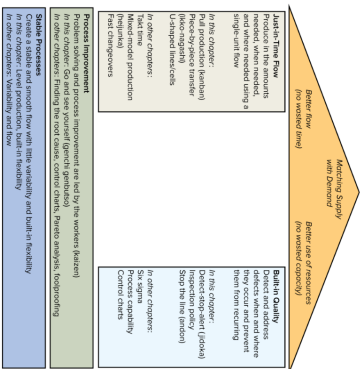


Figure 8.8 The TPS quality improvement framework

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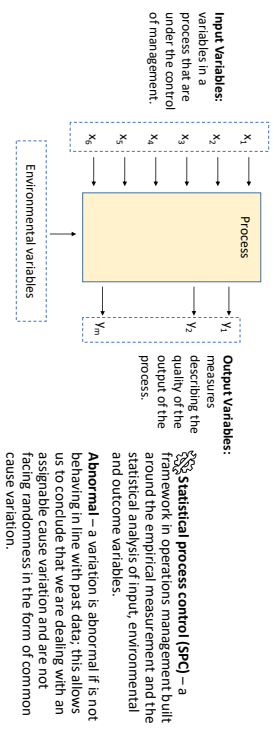


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Quality Framework

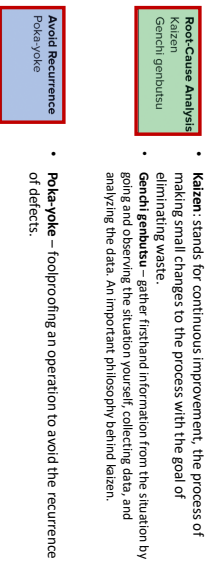


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TPS Pillar 2: Expose Problems & Solve Them When They Occur

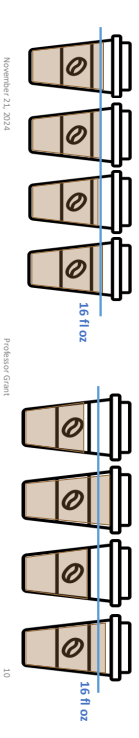


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- **Natural variation (common cause variation)** – occurs in a process as result of pure randomness
- **Assignable cause variation** – occurs because of a specific change in input or in environmental variables.
 - Undesirable, and avoidable, so we need to identify and eliminate the cause(s) for this type of variation



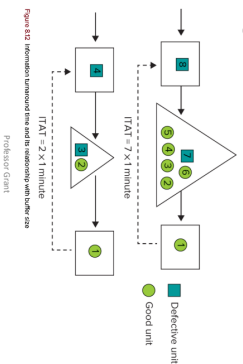
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Information turnaround time

Information turnaround time (ITAT) – the time between creating a defect and receiving the feedback about the defect

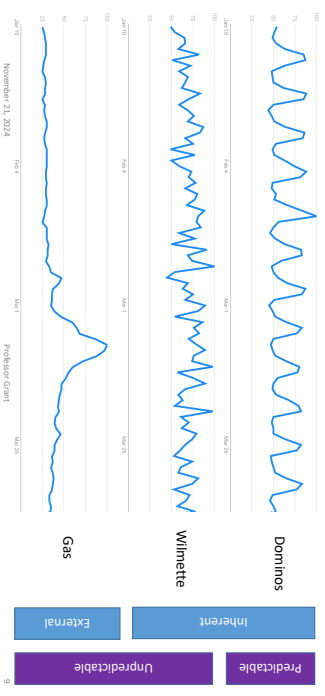


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Types of Variability (Google Searches)



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Process Capability Index

Process capability index – the ratio between the width of the specification interval of the outcome variable and the variation in the outcome variable (measured by six times its estimated standard deviation).

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

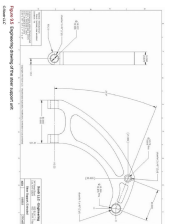
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Specification Limits

- **Lower specification limit (LSL)** – the smallest outcome value that does not trigger a defective unit.
- **Upper specification limit (USL)** – the largest outcome value that does not trigger a defective unit.
- **Specification width** – $USL - LSL$

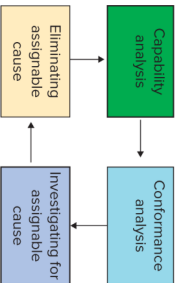


- USL = 80.000
- LSL = 79.900
- Specification Width = 80.000 - 79.900 = 0.1

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The Statistical Process Control Framework



- **Set of specifications** – a set of rules that determine if the outcome variable of a unit is defective or not.
- **Root cause** – a root cause for a defect is a change in an input or an environmental variable that initiated a defect.
- **Robust** – the ability of a process to tolerate changes in input and environmental variables without causing the outcomes to be defective.

Figure 9.2 Framework for statistical process control

Conformance Analysis

$$\bar{X} = \frac{x_1 + x_2 + \dots + x_n}{n}$$

X-bar-bar – The average of X-bars. A long-run center line which is the average across all points

- **Standard deviation** for all parts (across the 25 samples) given as 0.017846
- **Estimated Standard Deviation of X-bar:**
 - $ESD = \text{Standard deviation} / \sqrt{n}$
 - $ESD = 0.017846 / \sqrt{5} = 0.007981$

$$\begin{aligned} \text{UCL} &= \bar{X} + [3 \times \text{ESD}(\bar{X}\text{-bar})] = 79.951 + (3 \times 0.007981147) = 79.9749 \\ \text{LCL} &= \bar{X} - [3 \times \text{ESD}(\bar{X}\text{-bar})] = 79.951 - (3 \times 0.007981147) = 79.9271 \end{aligned}$$

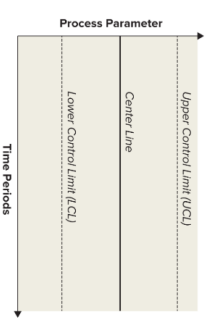
$$LCL = \bar{X} - [3 \times ESD(\bar{X})] = 79.951 - (3 \times 0.007981147) = 79.9271$$

Product	β_0	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8	β_9	β_{10}	β_{11}	β_{12}	β_{13}	β_{14}	β_{15}	β_{16}	β_{17}	β_{18}	β_{19}	β_{20}	β_{21}	β_{22}	β_{23}	β_{24}	β_{25}	β_{26}	β_{27}	β_{28}	β_{29}	β_{30}	β_{31}	β_{32}	β_{33}	β_{34}	β_{35}	β_{36}	β_{37}	β_{38}	β_{39}	β_{40}	β_{41}	β_{42}	β_{43}	β_{44}	β_{45}	β_{46}	β_{47}	β_{48}	β_{49}	β_{50}	β_{51}	β_{52}	β_{53}	β_{54}	β_{55}	β_{56}	β_{57}	β_{58}	β_{59}	β_{60}	β_{61}	β_{62}	β_{63}	β_{64}	β_{65}	β_{66}	β_{67}	β_{68}	β_{69}	β_{70}	β_{71}	β_{72}	β_{73}	β_{74}	β_{75}	β_{76}	β_{77}	β_{78}	β_{79}	β_{80}	β_{81}	β_{82}	β_{83}	β_{84}	β_{85}	β_{86}	β_{87}	β_{88}	β_{89}	β_{90}	β_{91}	β_{92}	β_{93}	β_{94}	β_{95}	β_{96}	β_{97}	β_{98}	β_{99}	β_{100}	β_{101}	β_{102}	β_{103}	β_{104}	β_{105}	β_{106}	β_{107}	β_{108}	β_{109}	β_{110}	β_{111}	β_{112}	β_{113}	β_{114}	β_{115}	β_{116}	β_{117}	β_{118}	β_{119}	β_{120}	β_{121}	β_{122}	β_{123}	β_{124}	β_{125}	β_{126}	β_{127}	β_{128}	β_{129}	β_{130}	β_{131}	β_{132}	β_{133}	β_{134}	β_{135}	β_{136}	β_{137}	β_{138}	β_{139}	β_{140}	β_{141}	β_{142}	β_{143}	β_{144}	β_{145}	β_{146}	β_{147}	β_{148}	β_{149}	β_{150}	β_{151}	β_{152}	β_{153}	β_{154}	β_{155}	β_{156}	β_{157}	β_{158}	β_{159}	β_{160}	β_{161}	β_{162}	β_{163}	β_{164}	β_{165}	β_{166}	β_{167}	β_{168}	β_{169}	β_{170}	β_{171}	β_{172}	β_{173}	β_{174}	β_{175}	β_{176}	β_{177}	β_{178}	β_{179}	β_{180}	β_{181}	β_{182}	β_{183}	β_{184}	β_{185}	β_{186}	β_{187}	β_{188}	β_{189}	β_{190}	β_{191}	β_{192}	β_{193}	β_{194}	β_{195}	β_{196}	β_{197}	β_{198}	β_{199}	β_{200}	β_{201}	β_{202}	β_{203}	β_{204}	β_{205}	β_{206}	β_{207}	β_{208}	β_{209}	β_{210}	β_{211}	β_{212}	β_{213}	β_{214}	β_{215}	β_{216}	β_{217}	β_{218}	β_{219}	β_{220}	β_{221}	β_{222}	β_{223}	β_{224}	β_{225}	β_{226}	β_{227}	β_{228}	β_{229}	β_{230}	β_{231}	β_{232}	β_{233}	β_{234}	β_{235}	β_{236}	β_{237}	β_{238}	β_{239}	β_{240}	β_{241}	β_{242}	β_{243}	β_{244}	β_{245}	β_{246}	β_{247}	β_{248}	β_{249}	β_{250}	β_{251}	β_{252}	β_{253}	β_{254}	β_{255}	β_{256}	β_{257}	β_{258}	β_{259}	β_{260}	β_{261}	β_{262}	β_{263}	β_{264}	β_{265}	β_{266}	β_{267}	β_{268}	β_{269}	β_{270}	β_{271}	β_{272}	β_{273}	β_{274}	β_{275}	β_{276}	β_{27
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Here, we have 25 samples,
each sample is of size 5
($n = 5$ observations per sample)

Control Chart

- Provides a visual representation of variation in the process.
 - Track process parameter over time
 - mean
 - percentage defects
 - Distinguish between
 - common cause variation (within control limits)
 - assignable cause variation (outside control limits)
 - **Lower control limit (LCL)** – a line in a control chart that provides the smallest value that is still acceptable without being labeled an abnormal variation.
 - **Upper control limit (UCL)** – a line in a control chart that provides the largest value that is still acceptable without being labeled an abnormal variation.
-



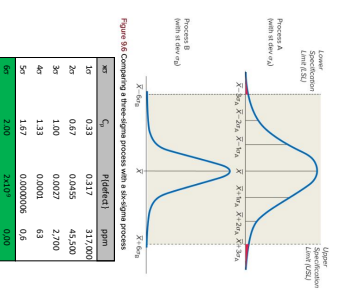
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Capability Analysis

- **Six-sigma program** – a process that has 6 standard deviations on either side of the mean and the specification limit.
- **Defect probability** – the statistical probability with which a randomly chosen flow unit does not meet specifications.
- **Parts per million** – the expected number of defective parts in a random sample of one million.
- **Target Variation** – the largest amount of variation in a process that does not exceed a given defect probability.



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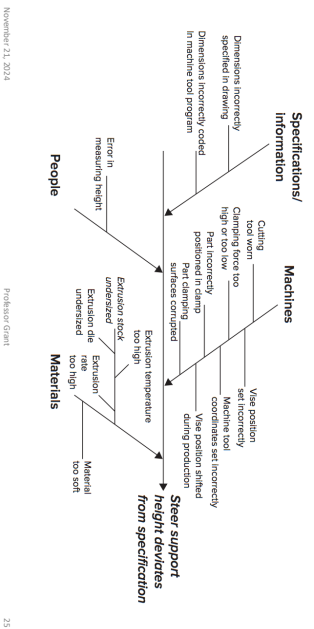
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Fishbone/Ishikawa/Cause-effect diagram



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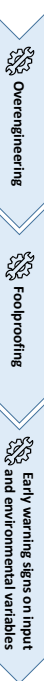
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How to Eliminate Assignable Causes and Make the Process More Robust



- **Overengineering**
Make the process so that it can do well, even under exceptional conditions.



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Investigating Assignable Causes

- Defect occurrence reflects some abnormal variation in the outcome variable.
- Result of abnormal variation in input or environmental variable
- Control Chart will alert that an assignable cause variation has occurred.
- Look for what input or environmental variables led to this result – investigate the root cause for the abnormal variation.
- How?

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Investigating Assignable Causes: Why

Five Whys – a brainstorming technique that helps employees to find the root cause of a problem, in order to avoid stopping too early and not having found the real root cause.

Why did this happen?

Was a potential cause the true root cause? Was it a symptom?

1. By asking “Why” five times, we can get to the underlying root cause as opposed to just dealing with the symptoms of the problems.
2. We can observe the responsible or root cause of the problem.

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X-bar Control Chart

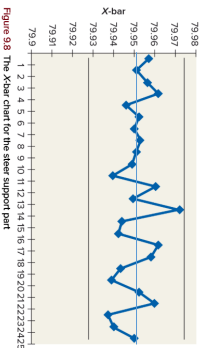


Figure 9.8 The X-bar chart for the steer support part

- If any sample is out of the control limits, then conclude the process is out of control.
- Also look for patterns to detect a behavior that may result in the process being out of control.
- Patterns to look for:
 - Is there a trend (upward or downward)?
 - Is there a long sequence of points above (or below) the center line?

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Pareto diagram

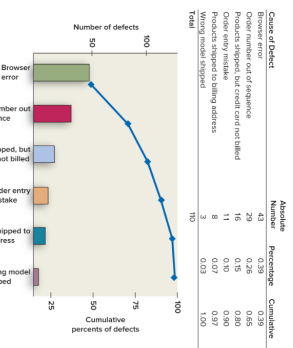


Figure 9.10 Root causes for various defects in order handling at Xoor

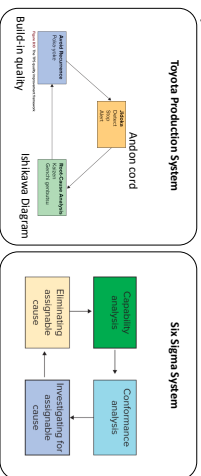
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Two (similar) Frameworks for Managing Quality



Some commonalities:

- Avoid defects by keeping variation out of the process
- If there is variation, create an alarm and trigger process improvement actions
- The process is never perfect – you keep on repeating these cycles