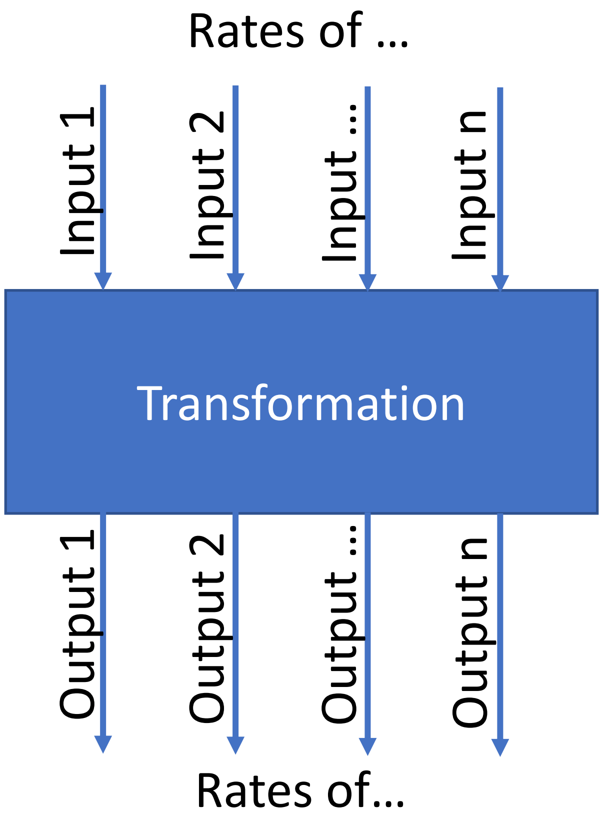
Frankfurt School

# 2023 Operations Management

# INTRODUCTION TO OPERATIONS MANAGEMENT

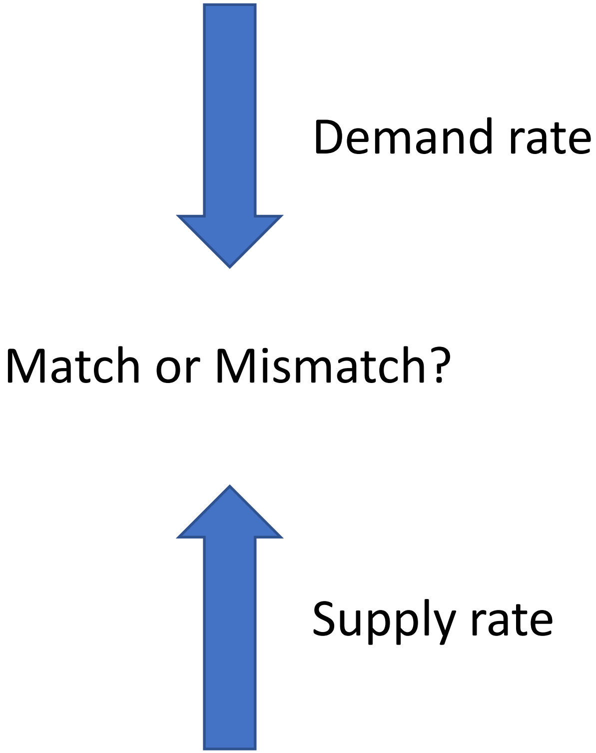
# What is Operations Management (OM)?

- Managing...
- ...the transformation of an input rate into an output rate (=supply rate)...
- ...to match a demand rate and make money or achieve non-for-profit objectives.

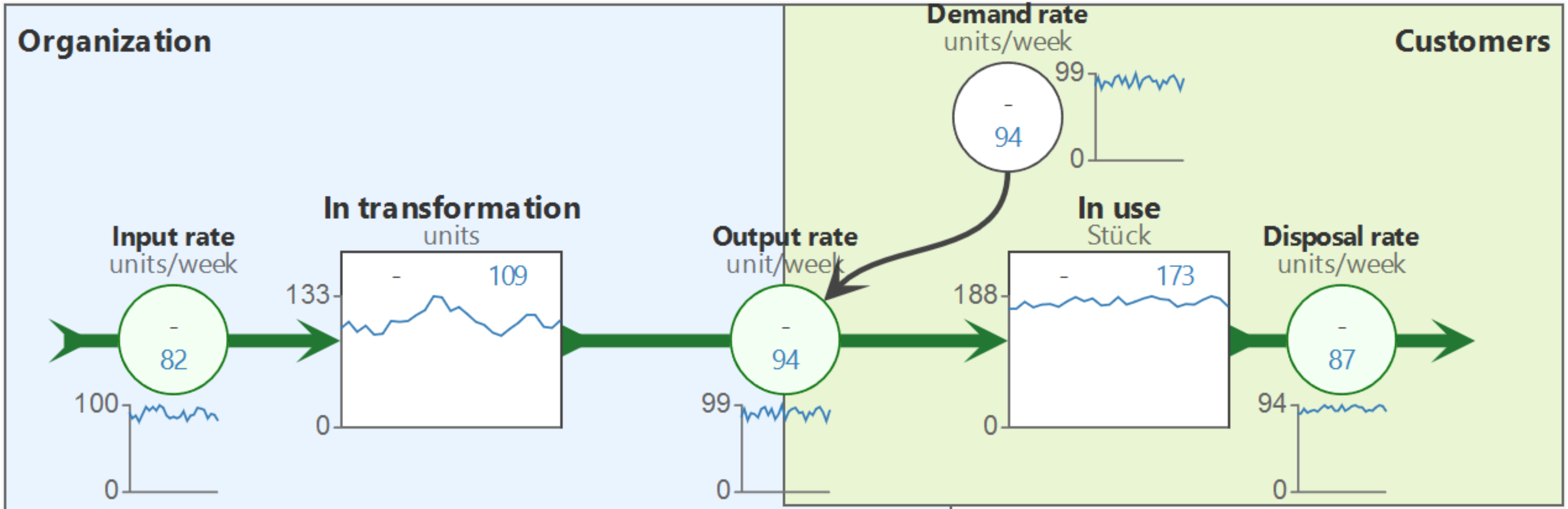


# Supply and Demand

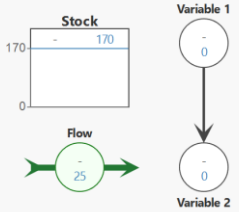
- Customer demand:
  rate of products or services requested by customers.
- Supply:
  rate of products or services provided by organizations (for-profit and non-for profit).



# OM – Managing the „Flow“




Symbols used
in stock-and-flow
diagrams



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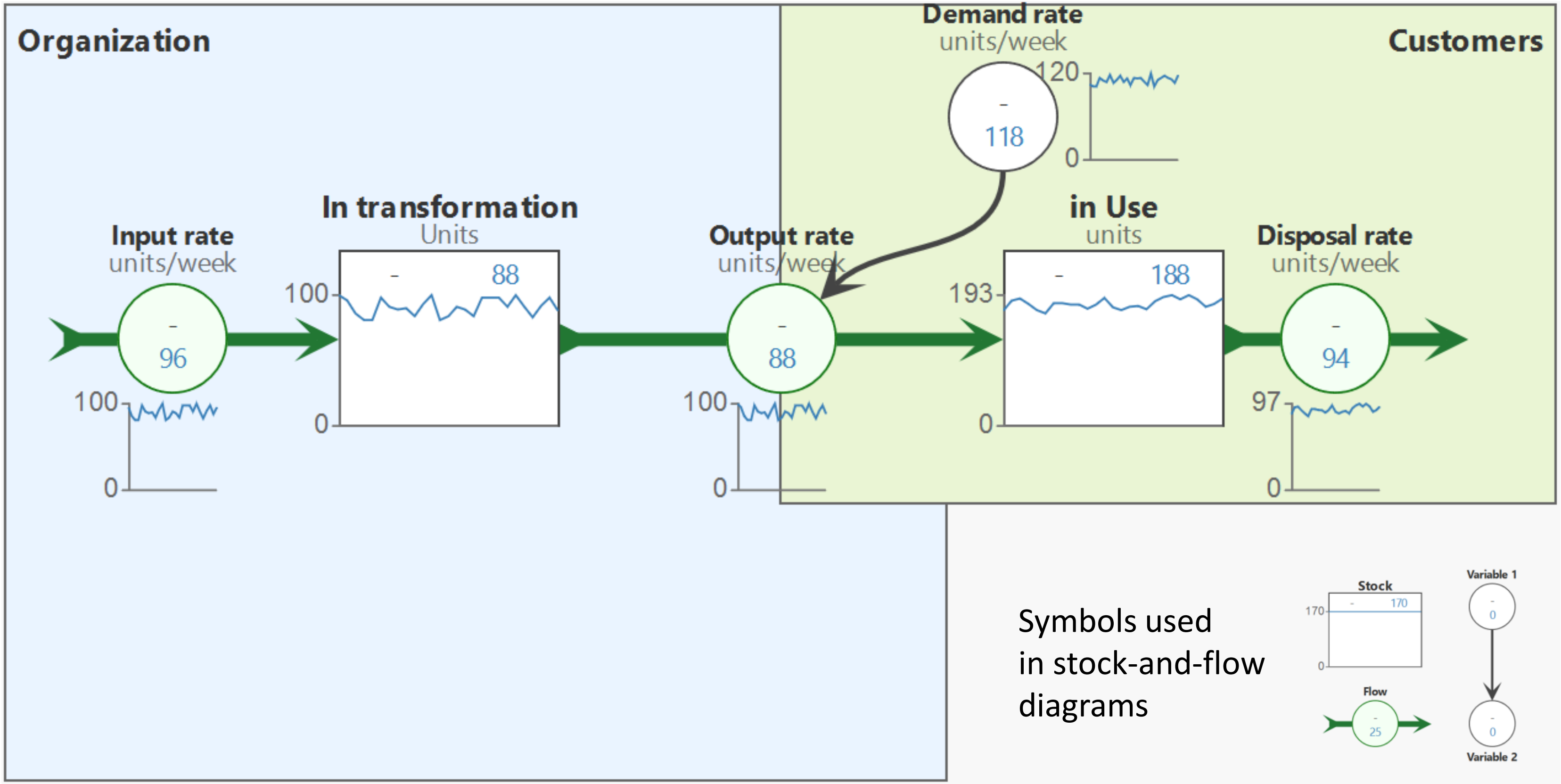
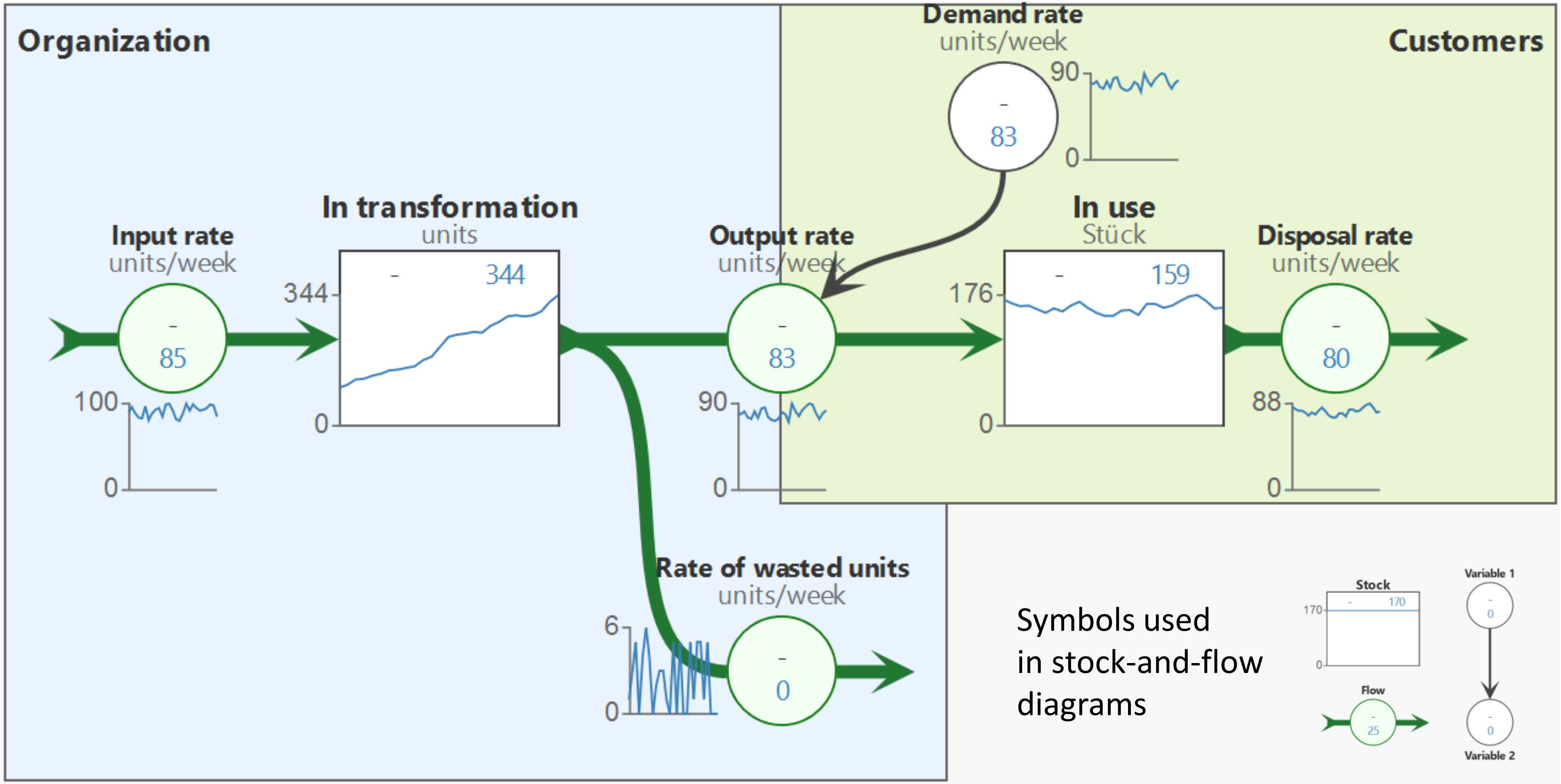


# OM – Managing the „Flow“



# HAIREXPRESS

- Professional hairdressing services at a very good price-performance ratio and quite spontaneous – while shopping;
- Enjoy your visit to the hairdresser without registration, in a friendly and fresh atmosphere;
- Our hairdressers specialize in fast cutting and service techniques and ensure that only the price, but not the quality, is saved.



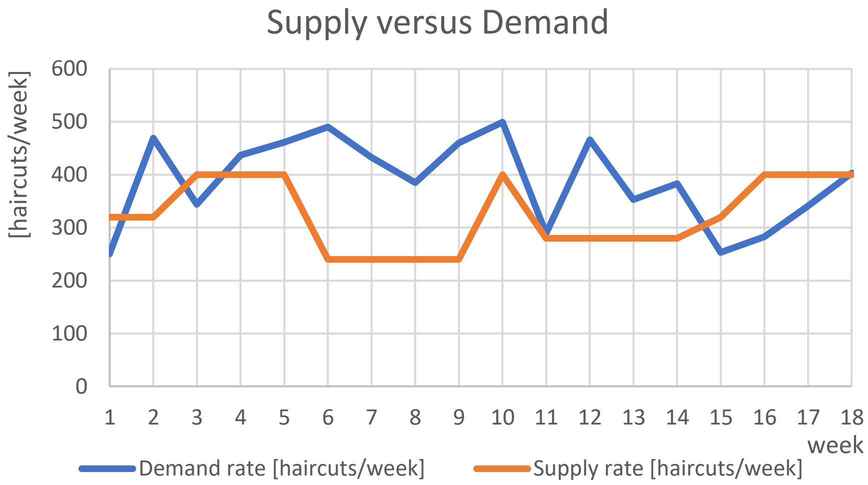

https://www.hairxpress.de/#about

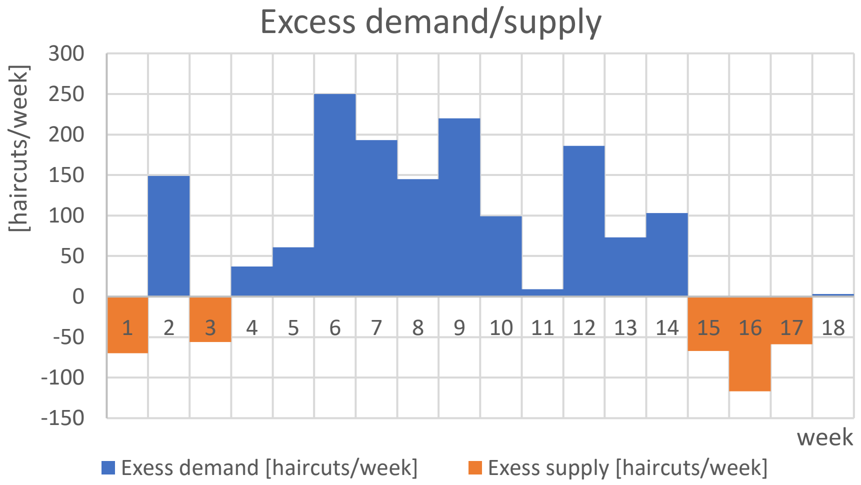
# HAIREXPRESS Challenges

- What is the consequence of supply-demand mismatch?
- What does the customer want out of the operations of such a type of hairdressing saloon?

# Supply-Demand Mismatch

- Excess demand
  - Theory: Price rice
  - Practice: Lost revenue
- Excess supply
  - Theory: Price fall
  - Practice: Resources are being wasted.



# HAIREXPRESS Challenges

- What is the consequence of supply-demand mismatch?
- What does the customer want out of the operations of such a type of hairdressing saloon?

# Consumer Utility at the Hairdresser

- Short hair, hair dye, perm;
- Hairstyling according to individual preferences;
- (Fair) price;
- A saloon nearby;
- Short waiting time.

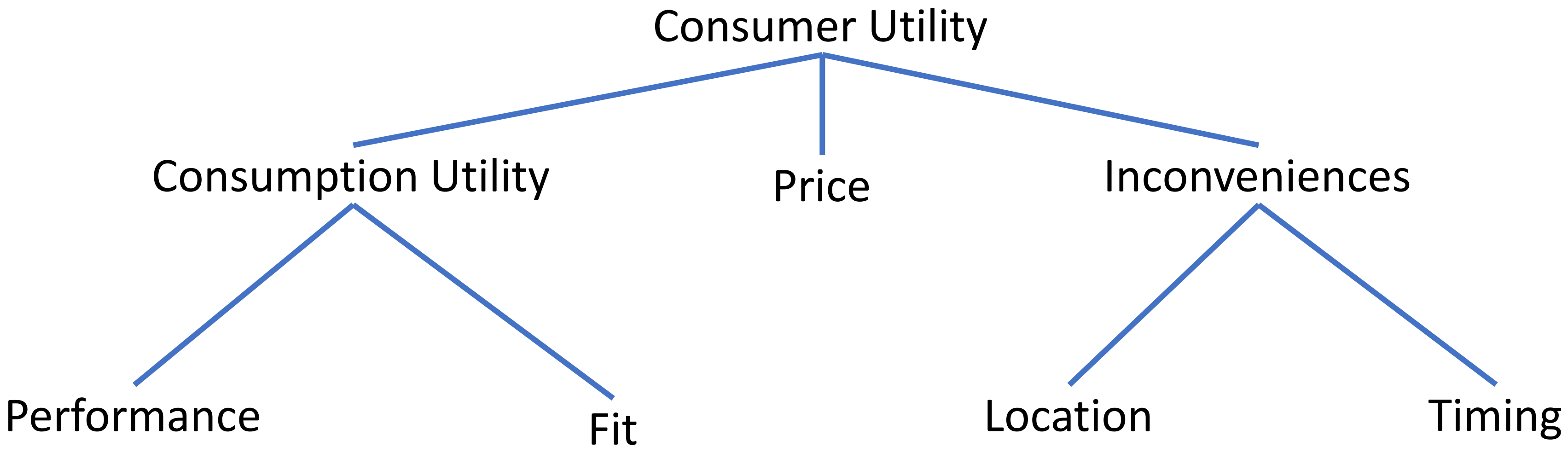
# A Second Example: Customer's Perspective

What does the customer want out of the operations of a mill (specialized on organic flour)?

# Consumer Utility at the Mill Shop

- Quantity (more is better, up to a certain limit);
- Fit of product attributes with individual preferences;
- (Fair) price;
- Short distance;
- Short lead time.

# Structuring Consumer Utility



# Classic Operations Performance Quadrangle

**Cost/Efficiency**

→ Are we wasting resources?

**Quality**

→ Are customers happy with the final product/service?

→ Are we delivering what we promise?

**Variety**

→ Are we providing sufficient variety to match the heterogeneous demands of our customers?

**Time**

→ How fast can we provide a service or product?

# From Operations Performance to Consumer Utility

**Cost/Efficiency**

Low Cost/high Efficiency
→ Good price

**Quality**

Good Quality
→ Good performance

**Variety**

Great Variety/Choice
→ Good fit with requirements

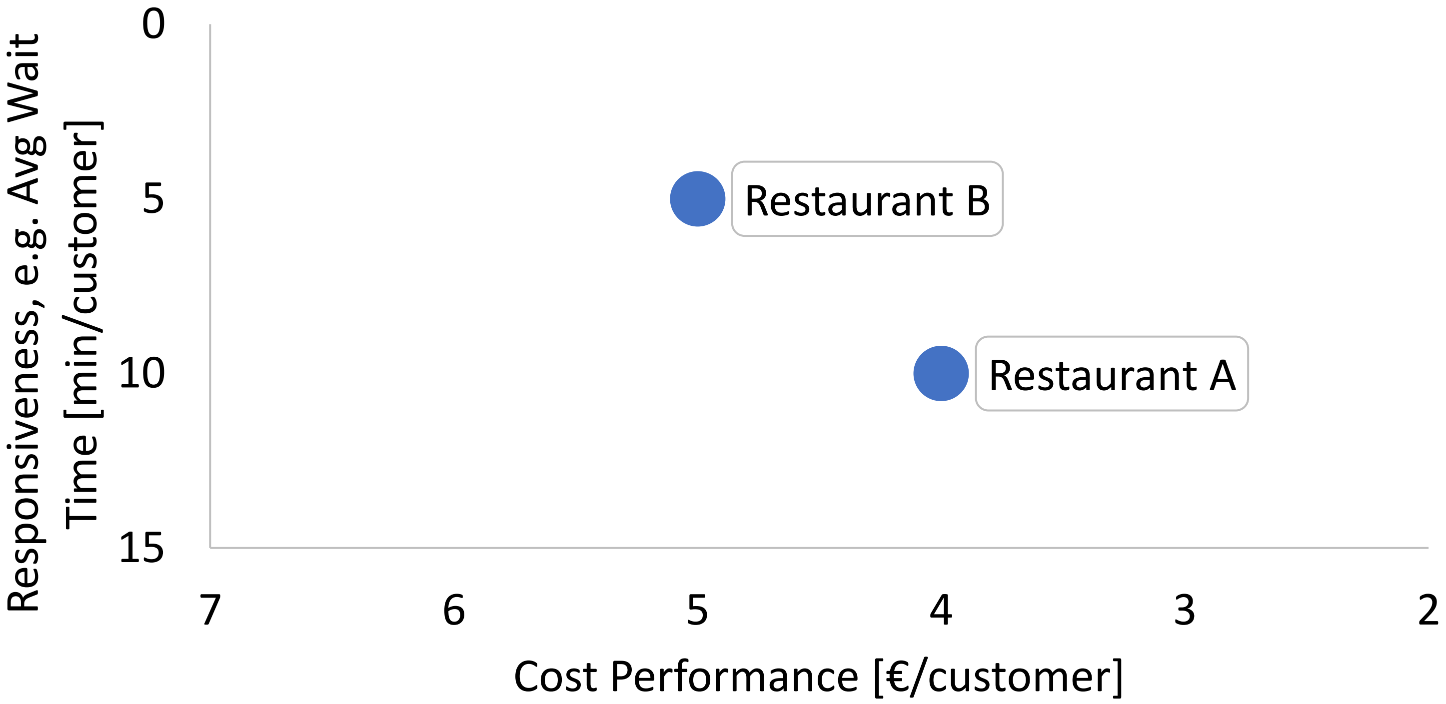
**Time**

Fast/Punctual Delivery
→ Right time

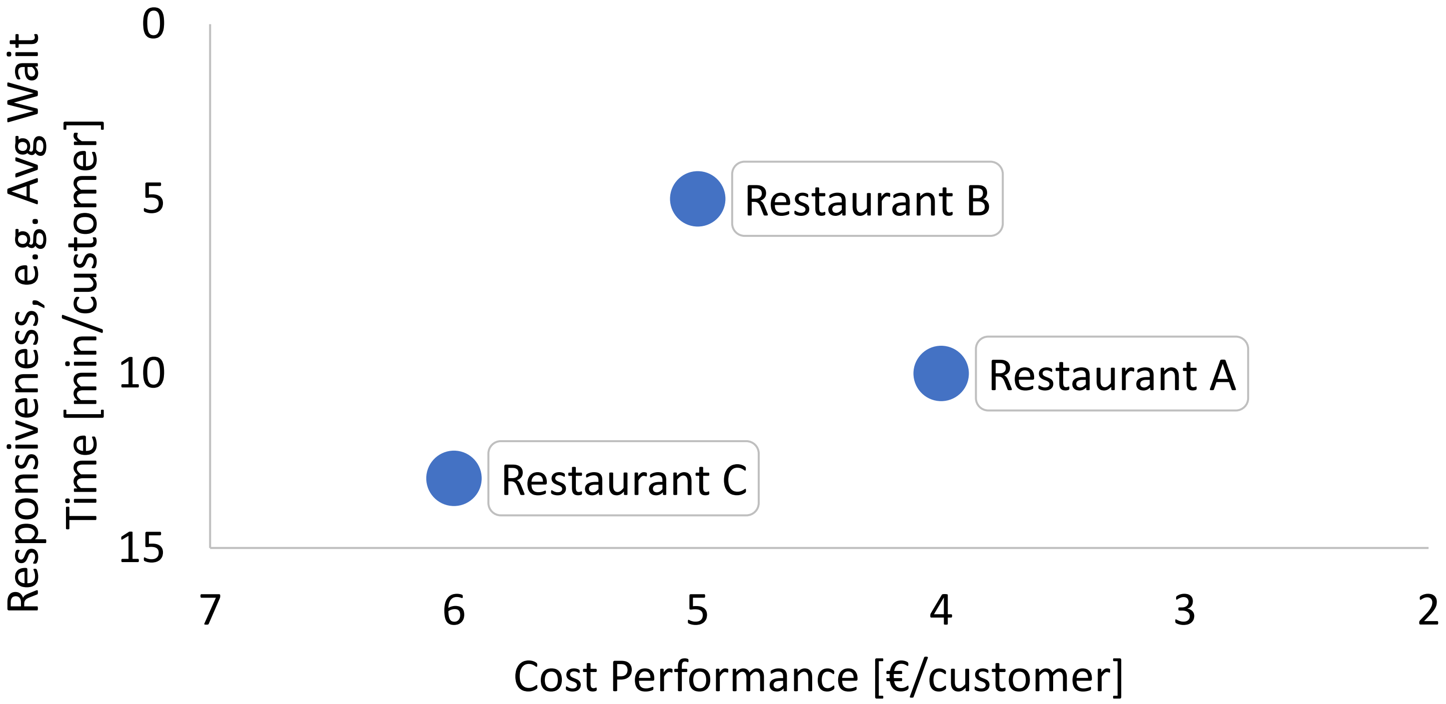
# Restaurant Challenges

- How to identify and overcome inefficiencies?
- How to manage strategic trade-offs?
- How to improve and innovate?

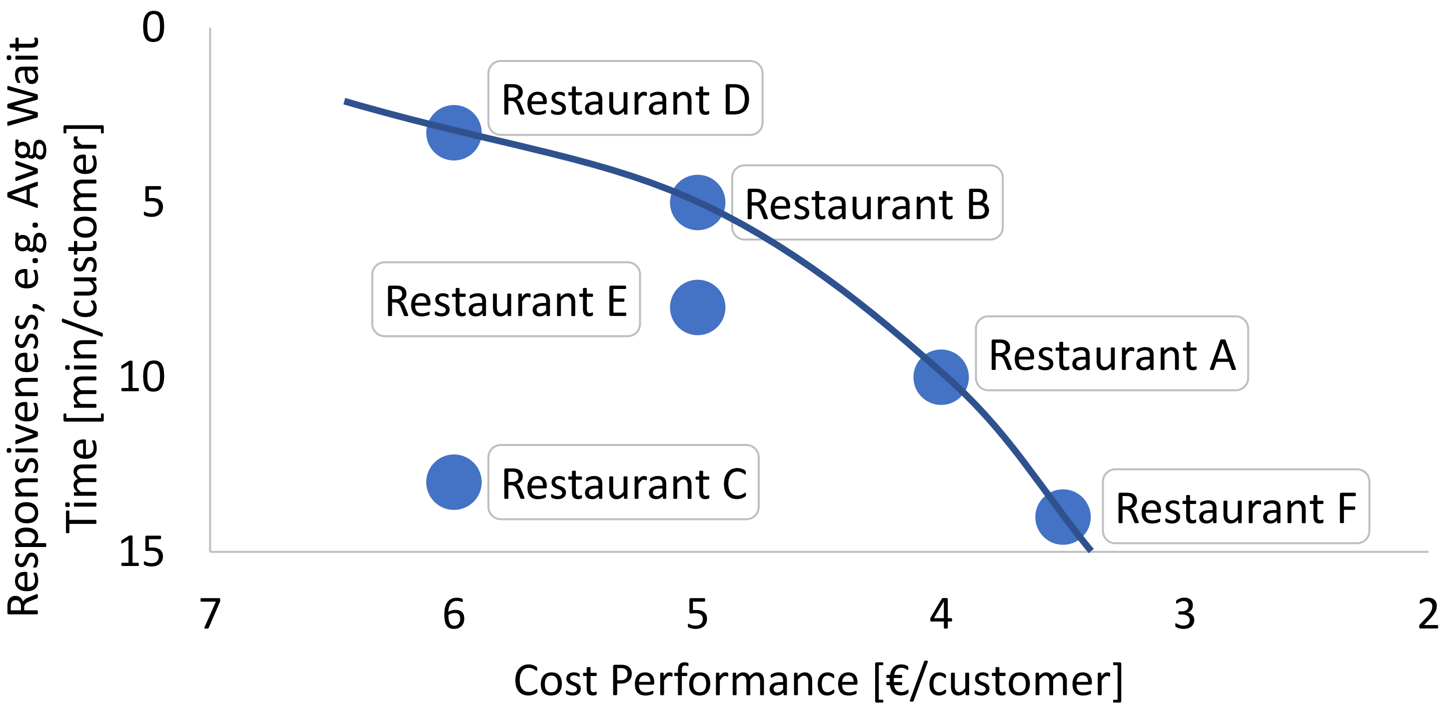
# Which Restaurant is in the Better Position?



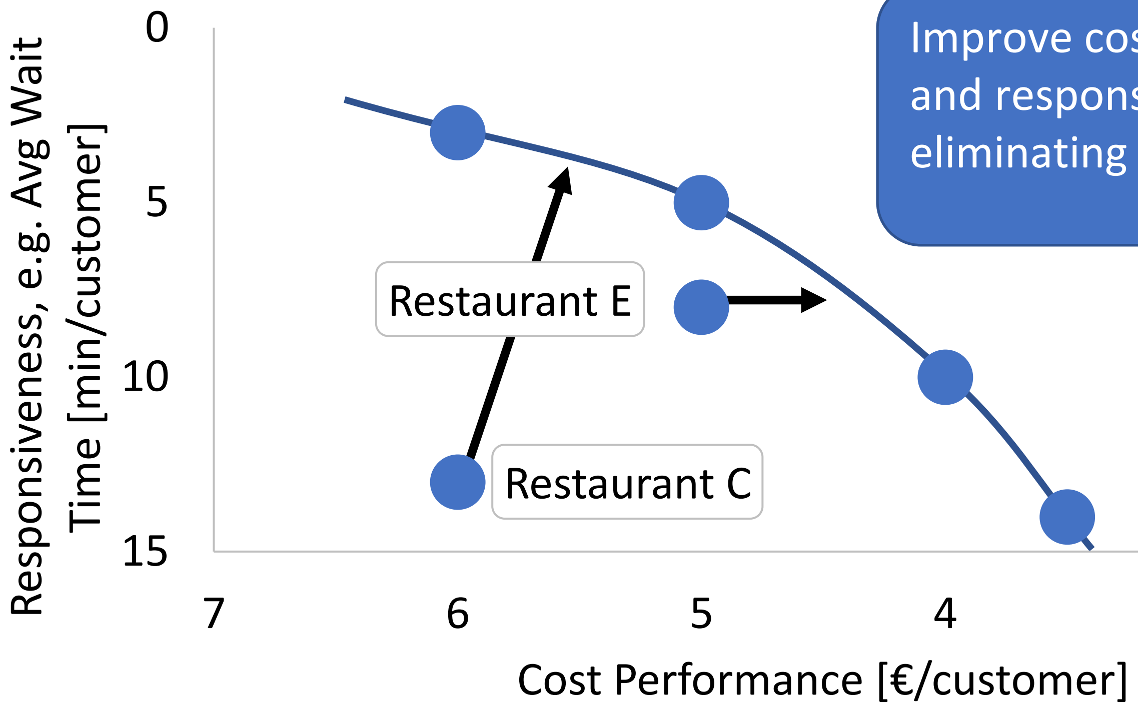
# What About Restaurant C?



# The Efficient Frontier



# Use OM to Overcome Inefficiencies

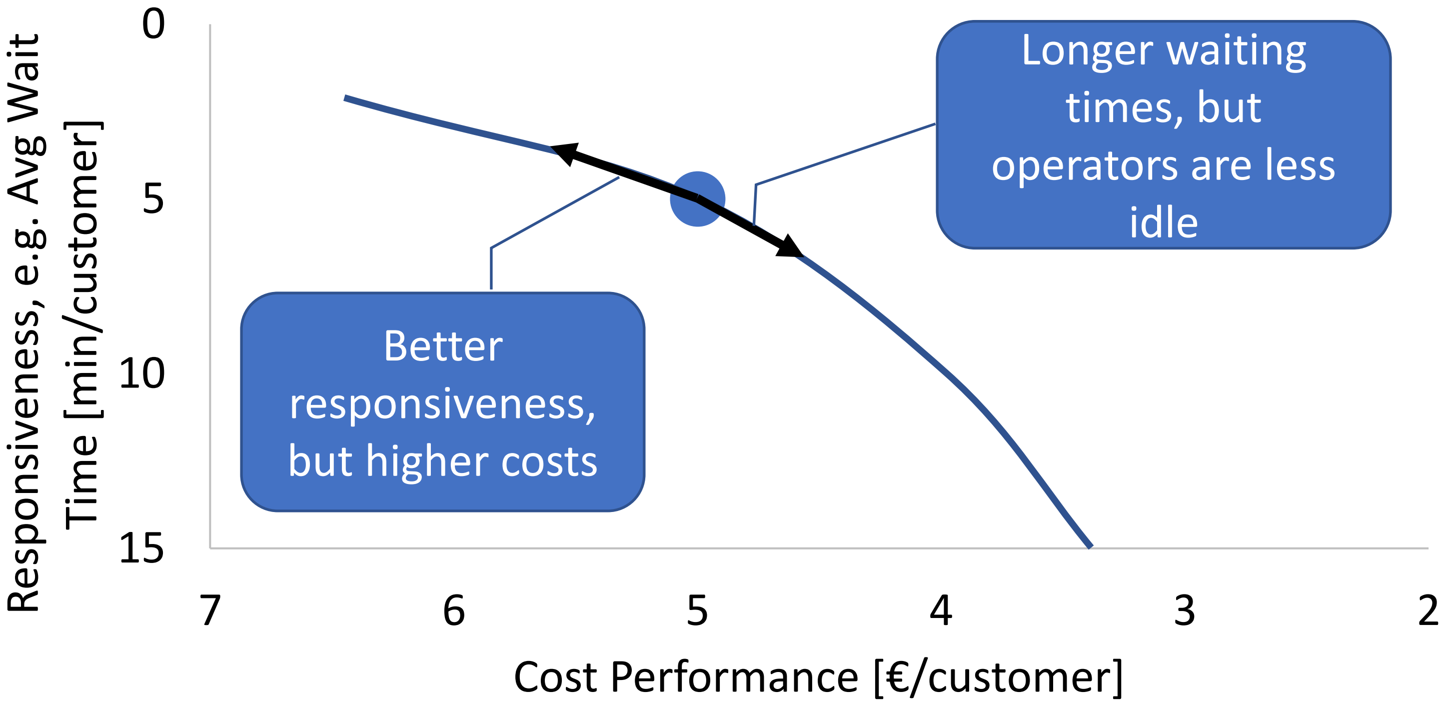



Improve cost performance and responsiveness by eliminating inefficiencies

# Restaurant Challenges

- How to identify and overcome inefficiencies?
- How to manage strategic trade-offs?
- How to improve and innovate?

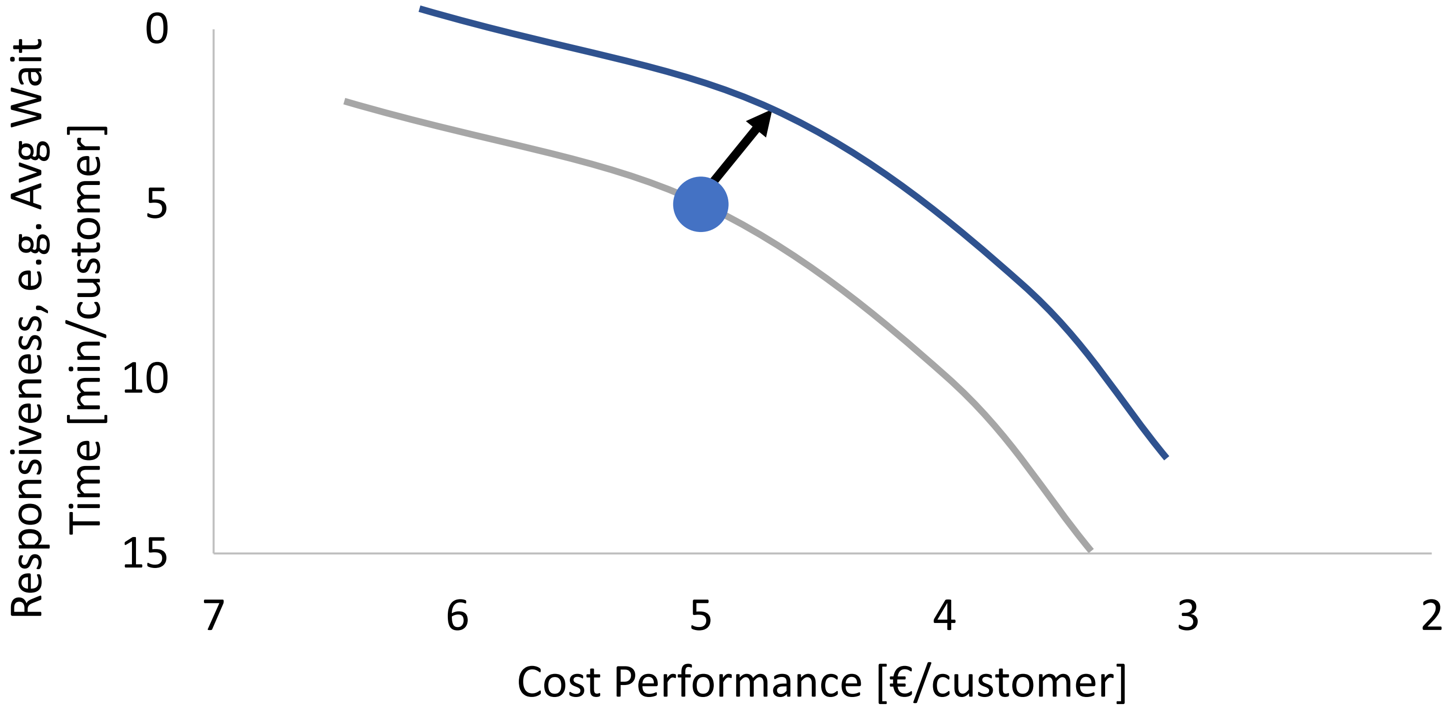
# Use OM to Support Strategic Trade-offs



# Restaurant Challenges

- How to identify and overcome inefficiencies?
- How to manage strategic trade-offs?
- How to improve and innovate?

# Use OM to Innovate and Improve



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# 2023 Operations Management

# INTRODUCTION TO PROCESSES

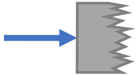
# Key Questions of a Manager of a Process

- Is the process performing well?
  → this session
- How can we make the process better?
  → subsequent sessions

# Characterizing a Process

- A process is an activity or a set of activities that accepts inputs and produces outputs.
- Processes require resources (employees, machines, etc.) to perform these activities.
- Processes can involve both goods and services.
- Processes can have multiple inputs and/or multiple outputs.


# Diagramming a Process

 Inputs flowing into a process

 Outputs flowing out of a process

 Single or multiple resources transforming inputs into outputs

# Process Flow Unit

- Basic unit that “flows” through the process.
- Start as input and later leave the process as output.
- Unit that gets processed using at least one resource.
- Generally associated with the outputs of a process.

students → University → alumni

Flow unit:

milk → Processing plant → milk powder

Flow unit:

people → Blood donation center → blood

Flow unit:

# Rules to Define Good Flow Units

A suitable flow unit…

- … corresponds to what you want to track and measure (with respect to the process).
- … remains fixed throughout the process (e.g., do not mix kg and tons of flour).
- … can be used to measure and describe all the activities within the process (e.g., minutes of workout could be better than km run/jumps accomplished).

# Process Analysis: Three Basic Measures

- **Inventory:** the number of flow units in the process at a given moment in time;
- **Flow Rate:** rate at which flow units leave the process (or enter* it);
- **Flow Time:** total time a flow unit spends in the process from start to finish.

| | Radiology | MBA Program | Wine Production |
|---|---|---|---|
| Flow unit | Patient | Student | Bottle |
| Inventory | $[Patient]$ | $[Student]$ | $[Bottle]$ |
| Flow rate | $\left[\frac{Patient}{Day}\right]$ | $\left[\frac{Student}{Year}\right]$ | $\left[\frac{Bottles}{Quarter}\right]$ |
| Flow time | $[Days]$ | $[Years]$ | $[Quarter]$ |

* in dynamic equilibrium

# Radiomedicum

- Reliable and fast diagnosis
- Pleasant atmosphere and modern practice rooms
- Focus on people
- At 7 locations in the Rhine-Main area and the Wetterau region


https://www.radiomedicum.de/

# Radiomedicum Challenges

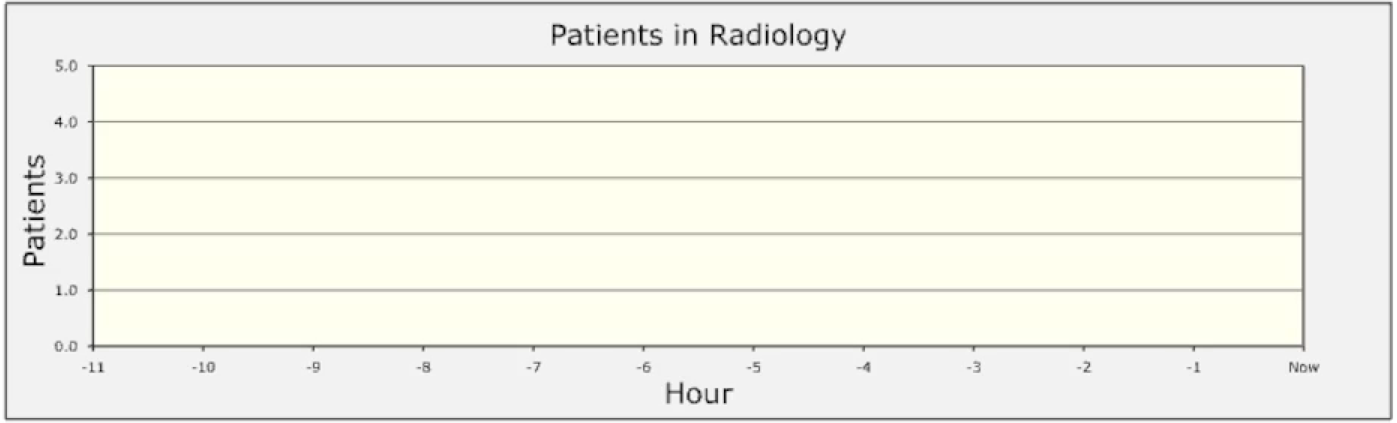
- How are flow time and flow rate determined?
- How is the stock level determined?


https://www.radiomedicum.de/

# Radiology

Patients arrive, get treated, and leave

07:30:00

# How to Determine the Measures for the Radiology?

Use a watch and capture arrival and departure times:

| Patient | Arrival | Departure |
|---|---|---|
| 1 | 07:35:00 | 08:50:00 |
| 2 | 07:45:00 | 10:05:00 |
| 3 | 08:10:00 | 10:10:00 |
| 4 | 09:30:00 | 11:15:00 |
| 5 | 10:15:00 | 10:30:00 |
| 6 | 10:30:00 | 13:35:00 |
| 7 | 11:05:00 | 13:15:00 |
| 8 | 12:35:00 | 15:05:00 |
| 9 | 14:30:00 | 18:10:00 |
| 10 | 14:35:00 | 15:45:00 |
| 11 | 14:40:00 | 17:20:00 |

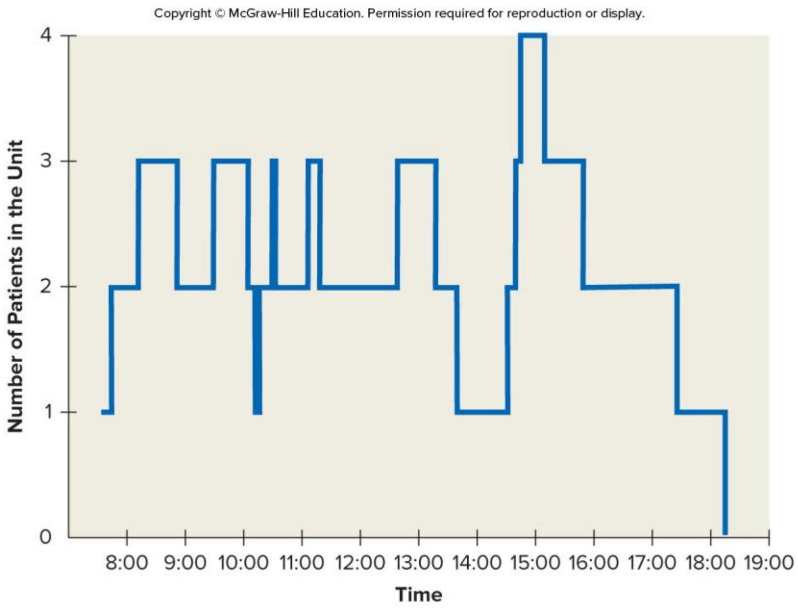
# Average Flow Time and Average Flow Rate

| Patient | Arrival [hh:mm:ss] | Departure [hh:mm:ss] | Flow Time [hh:mm:ss] |
|---|---|---|---|
| 1 | 07:35:00 | 08:50:00 | 01:15:00 |
| 2 | 07:45:00 | 10:05:00 | 02:20:00 |
| 3 | 08:10:00 | 10:10:00 | 02:00:00 |
| 4 | 09:30:00 | 11:15:00 | 01:45:00 |
| 5 | 10:15:00 | 10:30:00 | 00:15:00 |
| 6 | 10:30:00 | 13:35:00 | 03:05:00 |
| 7 | 11:05:00 | 13:15:00 | 02:10:00 |
| 8 | 12:35:00 | 15:05:00 | 02:30:00 |
| 9 | 14:30:00 | 18:10:00 | 03:40:00 |
| 10 | 14:35:00 | 15:45:00 | 01:10:00 |
| 11 | 14:40:00 | 17:20:00 | 02:40:00 |

| | | |
|---|---|---|
| Arrival of first patient | 07:35:00 | [hh:mm:ss] |
| Departure of last patient | 18:10:00 | [hh:mm:ss] |
| Length of day | 10:35:00 | [hh:mm:ss] |
| Length of day | 10,583 | [hours] |
| Patient per day | 11 | [patient/day] |
| Ø Average flow rate | 1,04 | [patient/hour] |
| Ø Average flow time | 02:04:33 | [hh:mm:ss] |
| Ø Average flow time | 2,08 | [hours] |

# Average Inventory

- Straightforward to graph inventory of patients using the arrival and departure data;
- Not straightforward to calculate average inventory;
- Weighing the number of patients in radiology with the time span leads to 2.16 [patients].




Number of patients in Radiology

# Fortunately, there is…

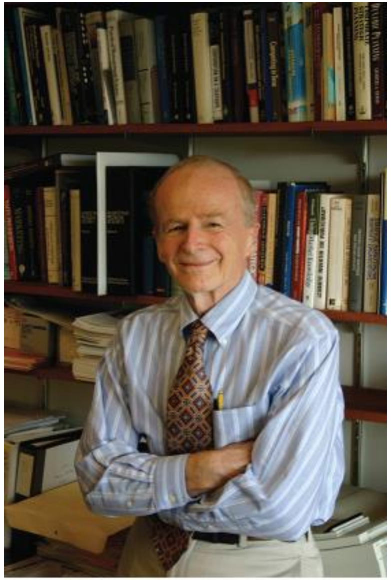
…a relationship between flow rate, flow time and inventory named…

$$Average\ Flow\ Rate\ R = 1.04\ \left[\frac{patients}{hour}\right]$$

$$Average\ Flow\ Time\ T = 2.08\ [hour]$$

$$Average\ Inventory\ I = 2.16\ [patients]$$

$$I = R \cdot T$$



©John D. Little

**…Little's Law.**

Little, J.D., 1961. A proof for the queuing formula. *Operations Research*, *9*(3), pp.383-387.

# Little’s Law

- Descriptively simple, but remarkably powerful;
- It holds for any distributions of R and T;
- It applies to any system, particularly, it applies to systems within systems;
- Only requirement: system must be in dynamic equilibrium (stable).

The long-term average number I of flow units in a stationary system is equal to the long-term average flow rate R multiplied by the average flow time T that a flow unit spends in the system.

# Little’s Law

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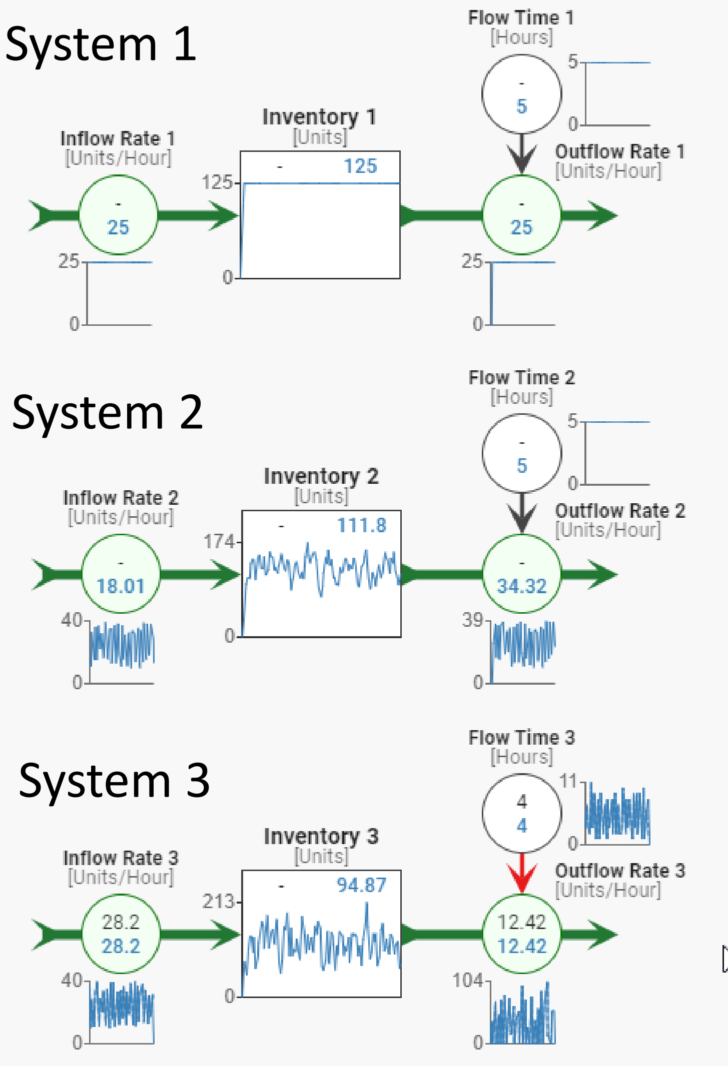


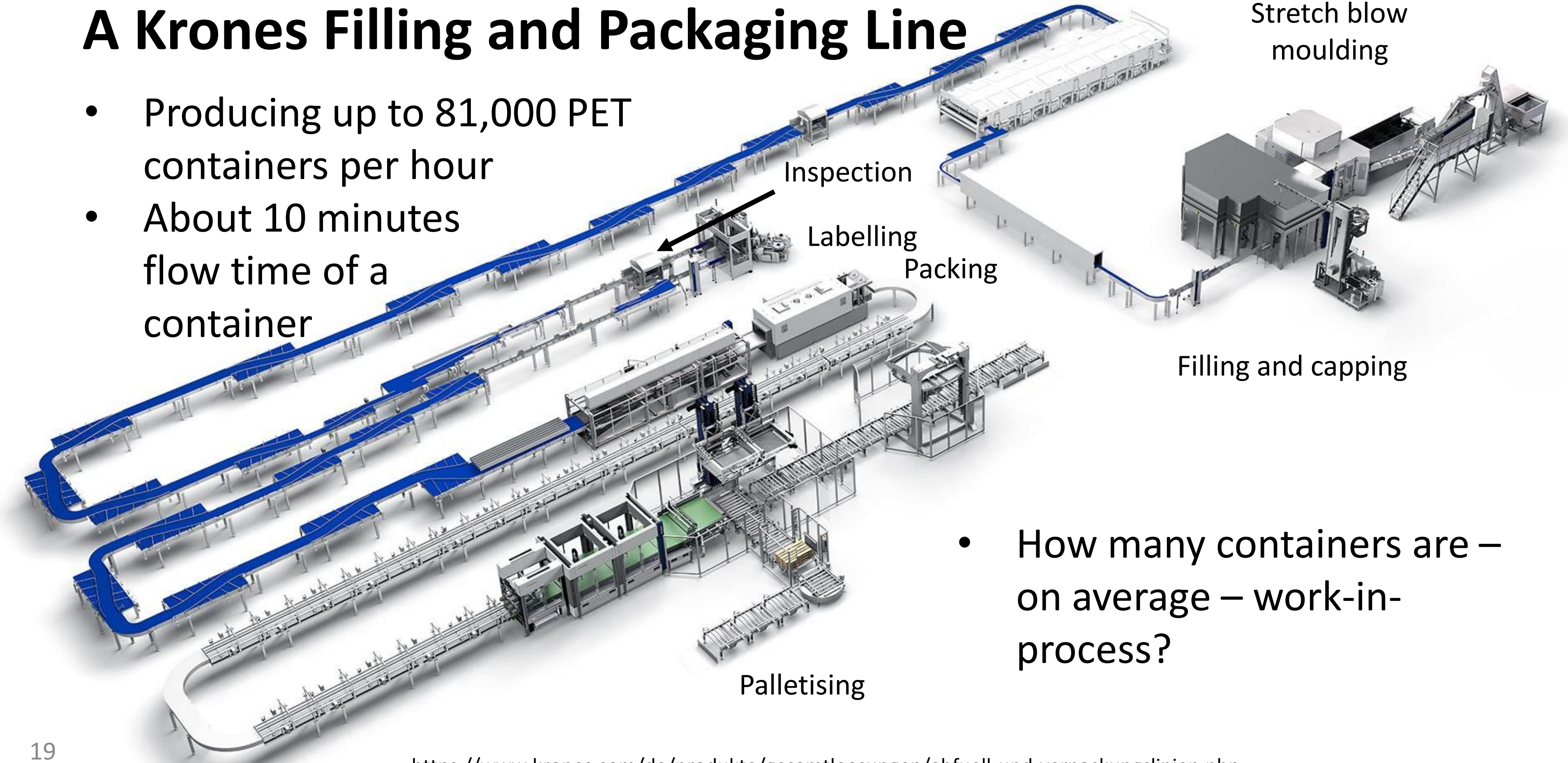
# Krones

- Founded in 1951 as a manufacturer of labelling machines.
- Headquarters of Krones AG are located in Neutraubling near Regensburg.
- Today, Krones delivers leading technologies for filling and packaging

https://www.krones.com/en/

# A Krones Filling and Packaging Line

- Producing up to 81,000 PET containers per hour
- About 10 minutes flow time of a container




- How many containers are – on average – work-in-process?

https://www.krones.com/de/produkte/gesamtloesungen/abfuell-und-verpackungslinien.php

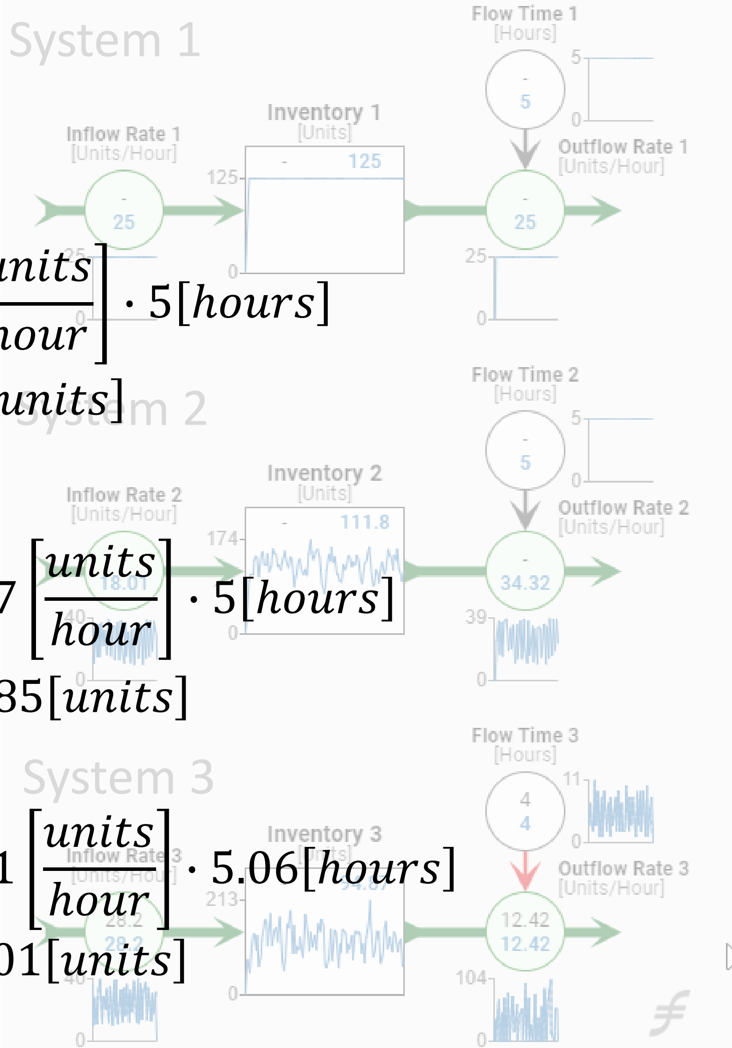
# BACKUP

# Little’s Law Tested

| System 1 Descriptive Data (N=190) | |
|---|---|
| Average Inventory | 125 [units] |
| Average Inflow Rate | 25 [units/hour] |
| Average Outflow Rate | 25 [units/hour] |
| Average Flow Time | 5.00 [hour] |

| System 2 Descriptive Data (N=190) | |
|---|---|
| Average Inventory | 127.16 [units] |
| Average Inflow Rate | 25.37 [units/hour] |
| Average Outflow Rate | 25.47 [units/hour] |
| Average Flow Time | 5.00 [hour] |

| System 3 Descriptive Data (N=190) | |
|---|---|
| Average Inventory | 121.08 [units] |
| Average Inflow Rate | 24.31 [units/hour] |
| Average Outflow Rate | 24.58 [units/hour] |
| Average Flow Time | 5.06 [hour] |




$$I = 25\left[\frac{units}{hour}\right] \cdot 5[hours]$$

$$I = 125[units]$$

$$I = 25.37\left[\frac{units}{hour}\right] \cdot 5[hours]$$

$$I = 126.85[units]$$

$$I = 24.31\left[\frac{units}{hour}\right] \cdot 5.06[hours]$$

$$I = 123.01[units]$$

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# 2023 Operations Management

# PROCESS ANALYSIS

# PROCESS ANALYSIS AND PROCESS FLOW DIAGRAM

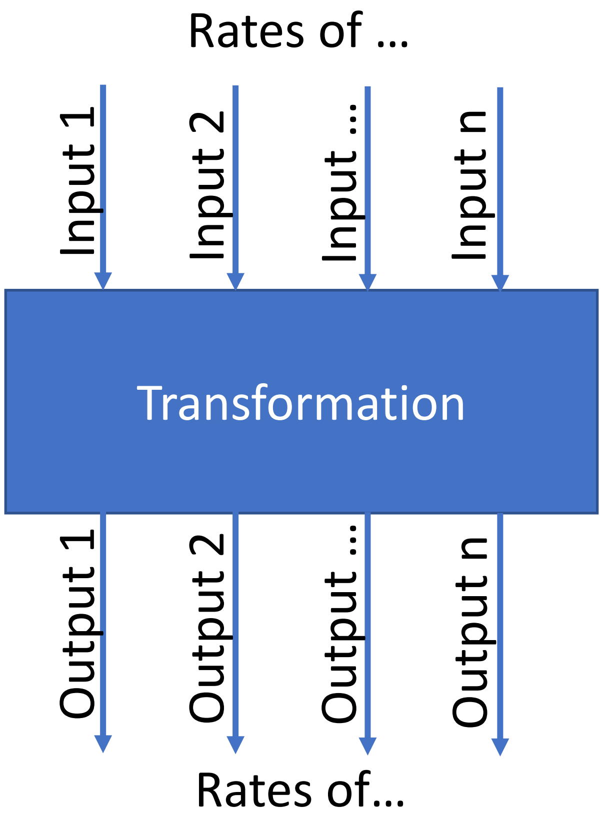
# Process Analysis

- Addressing the question

  “How can we improve a process?”

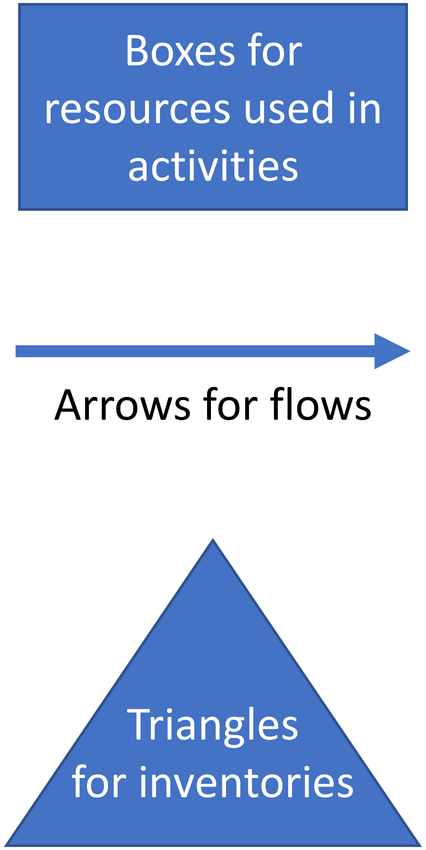
  requires to open the “black box” of transformation.

- Process analysis provides a rigorous framework for understanding the detailed operations of an organization.

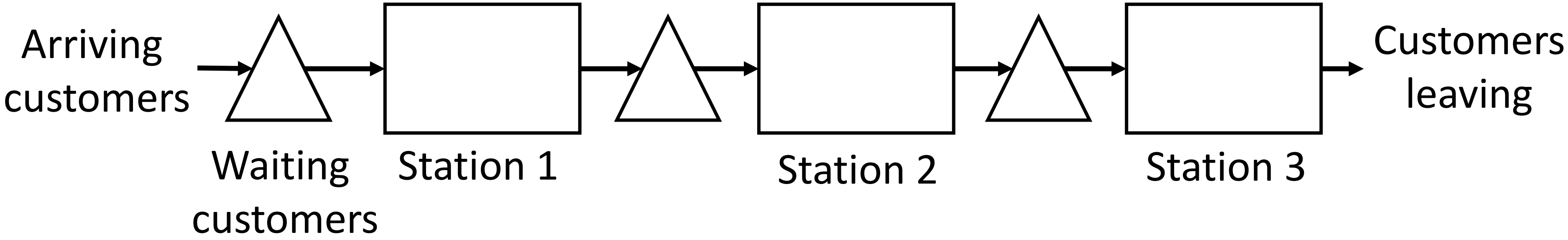


# Process Flow Diagram

- The best way to begin any process analysis:  drawing a Process Flow Diagram.
- A process flow diagram is a graphical way to describe important (not all) details of a process.
- It focuses on flows, resources and inventory.



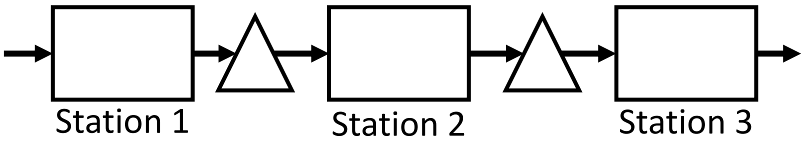
# A Simple Example

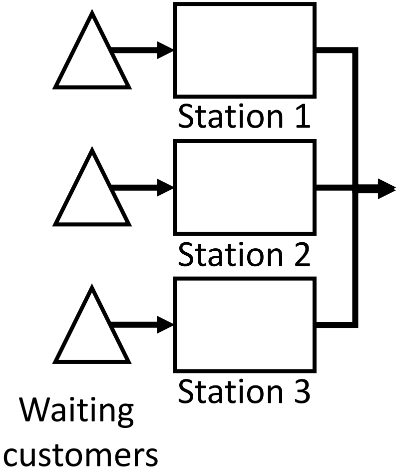


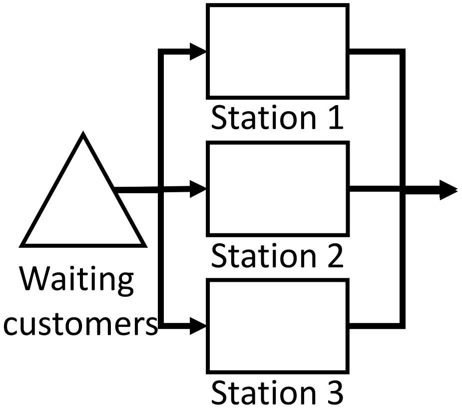

Upstream – the parts of the process that are at the beginning of the process flow

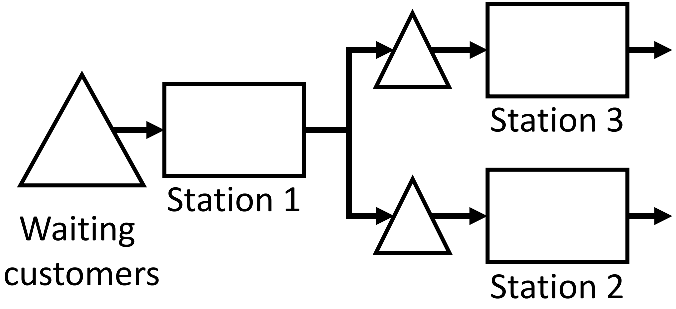
Downstream – the parts of the process that are at the end of the process flow

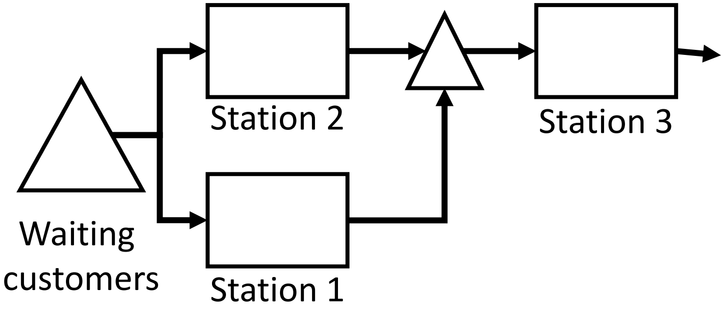
# Alternate Process Designs



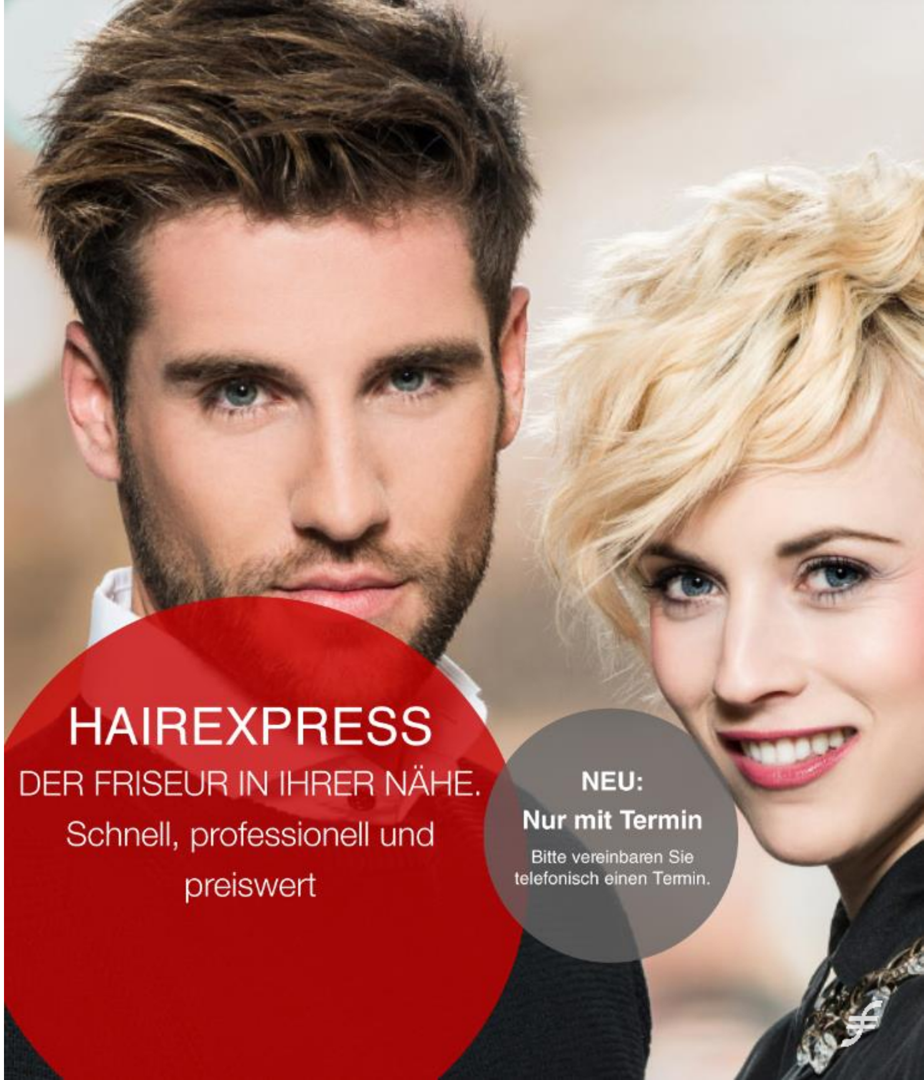



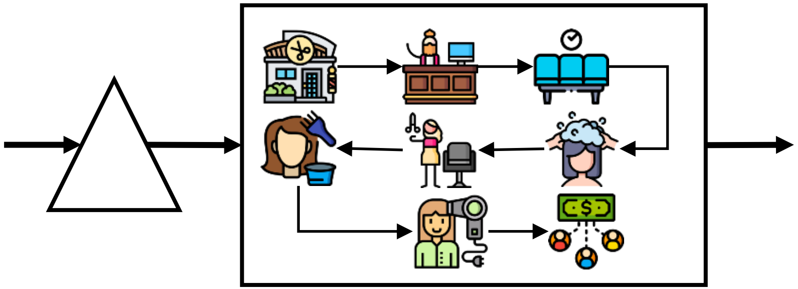
# ONE-STEP PROCESSES

# HAIREXPRESS
# Challenges

- What is the capacity of a one-step process?
- What is the flow rate, the utilization, and the cycle time of a process?



# Hairdressing as One-Step Process



Hairdressing

- One-step processes can include multiple activities.
- One employee (one resource) is in charge of the complete service process.

# Activities Included in the Hairdressing Process

| Activity | Activity Time [min/customer] |
|---|---|
| Welcome the customer | 2.0 |
| Check-in the customer and place them in the waiting area | 6.5 |
| Seat the customer and wash the hair | 7.0 |
| Cut customer's hair | 9.5 |
| Color customer's hair | 10.0 |
| Dry and style the hair and check overall appearance | 15.0 |
| Check-out (advertising and selling of hairdressing products, paying of the bill, new appointment) | 4.5 |
| Total | 54.5 |

All activities are performed by the same employee (resource).

Total activity time = processing time = 54.5 min/customer.

Be very careful with units!

# Processing Time versus Flow Time

- Flow time of one flow unit = End time of last activity – Start time of first activity

9:00
Start time
first activity

Flow time of one customer: 54:30 [mm:ss]
54.50 [min]

9:54:30
End time
Last activity

- Processing time of a resource:
  Time required by a resource to process flow units

Example Hairexpress:
A hairdresser works 54.50 min to serve a customer from start to end.

$$Processing\ time = 54.50\,\frac{hairdresser \cdot min}{customer}$$

# Capacity of a Resource

- Maximum amount that a resource can produce in a given amount of time. (= maximum flow rate).
- Measured in flow units per time period.
- Different time units can be used (seconds, minutes, hours, days, weeks, month, quarters, years, …).
- Basis for a multitude of important performance measures.


$$Capacity = \frac{1\ resource\ unit}{resource\ processing\ time}$$

$$Capacity = \frac{1}{Processing\ time}$$

The "1" in the formula means that one unit of a resource is used, so that one flow unit can be processed/served at the same time.

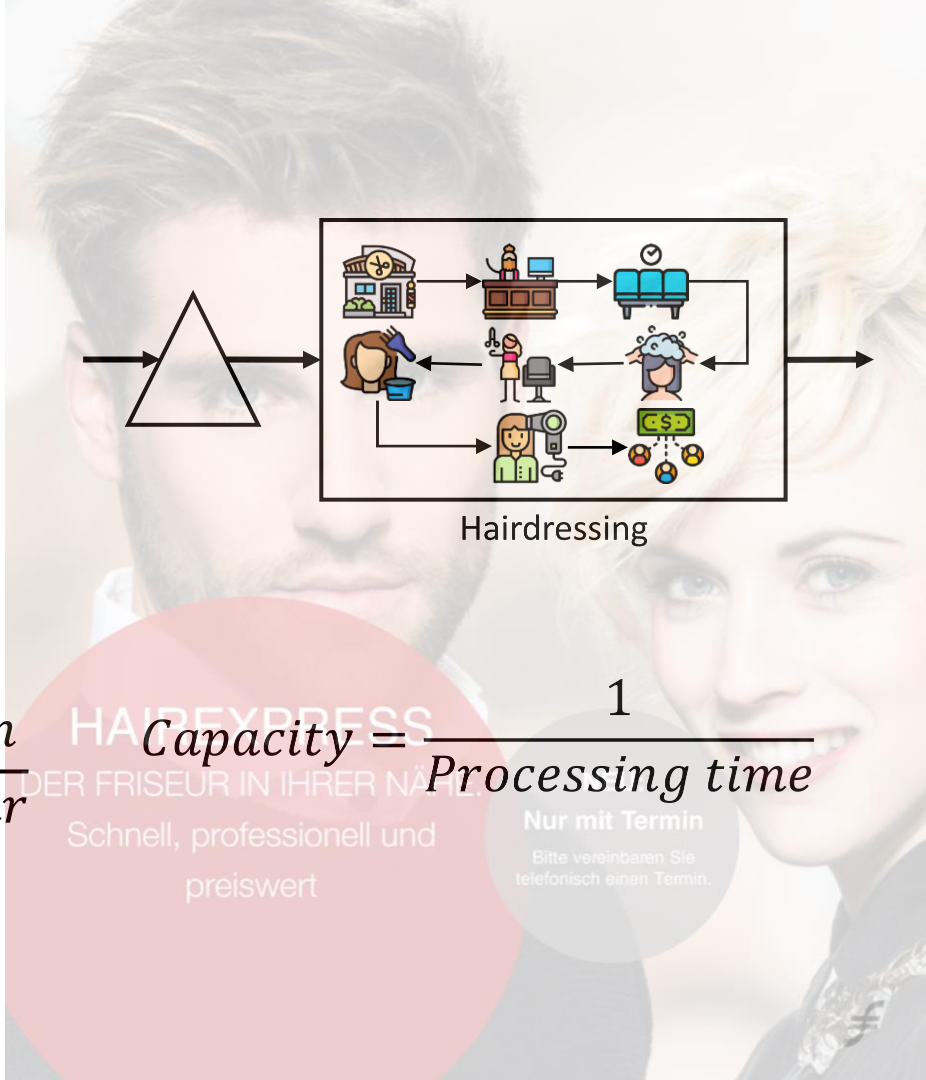
# Capacity of a Hairexpress-hairdresser

$$Capacity = \frac{1\ hairdresser}{54.5\ \frac{hairdresser \cdot min}{customer}}$$

$$Capacity = 0.0183\ \frac{customers}{min}$$

$$= 0.0183\ \frac{customers}{min} \cdot 60\ \frac{min}{hour}$$

$$= 1.1009\ \frac{customers}{hour}$$





$$Capacity = \frac{1}{Processing\ time}$$

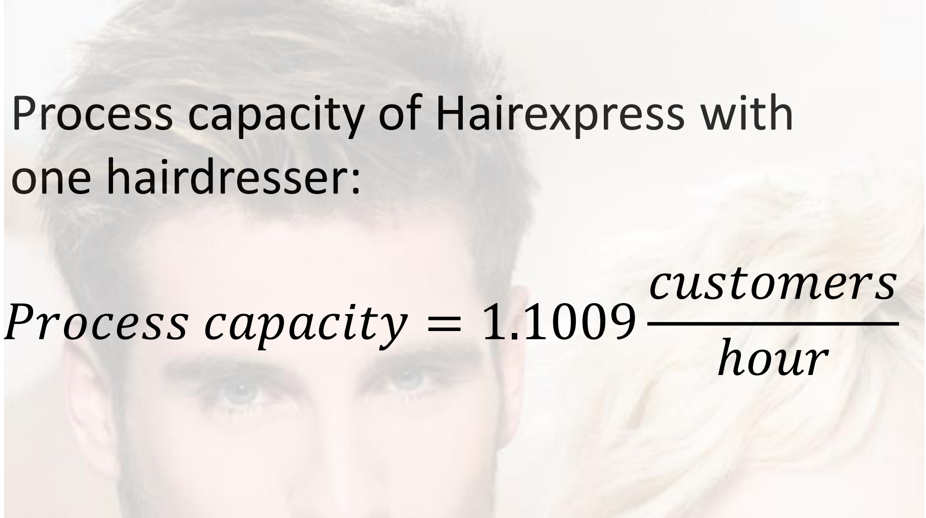
# Process Capacity

- Maximum amount that a process can produce in a given amount of time. (= maximum flow rate).
- One-step process with one resource:

$$Process\ capacity = Capacity\ of\ the\ resource$$

- One-step process with multiple resources:

$$Process\ capacity = \min \begin{Bmatrix} Capacity_1, \\ Capacity_2, \\ \dots \\ Capacity_n \end{Bmatrix}$$

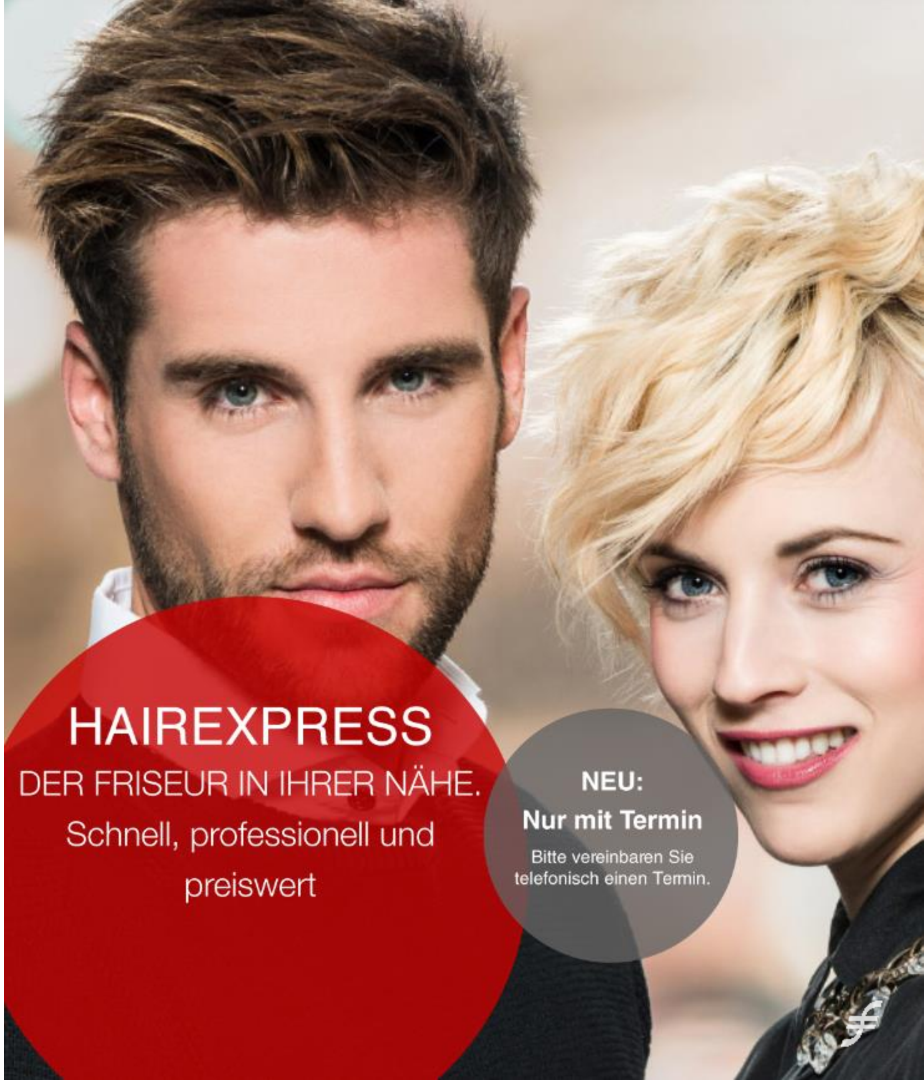


Process capacity of Hairexpress with one hairdresser:

$$Process\ capacity = 1.1009 \frac{customers}{hour}$$

# HAIREXPRESS Challenges

- What is the capacity of a one-step process?
- **What is the flow rate, the utilization, and the cycle time of a process?**



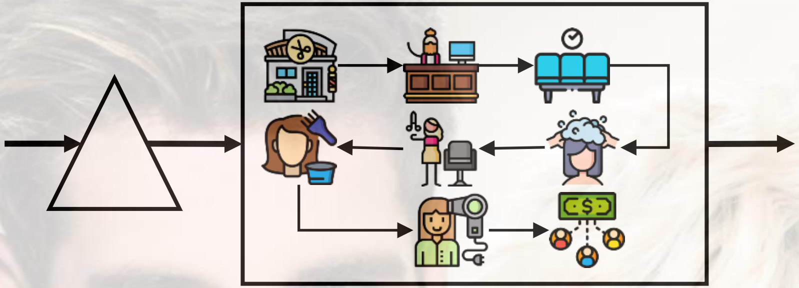
# Flow Rate

$$Demand\ rate = 12\ \frac{customers}{hour}$$

$$Process\ capacity = 1.1009\ \frac{customers}{hour}$$

$$Flow\ rate = min\begin{Bmatrix} 12\ \frac{customers}{hour}, \\ 1.1009\ \frac{customers}{hour} \end{Bmatrix}$$

$$Flow\ rate = 1.1009\ \frac{customers}{hour}$$

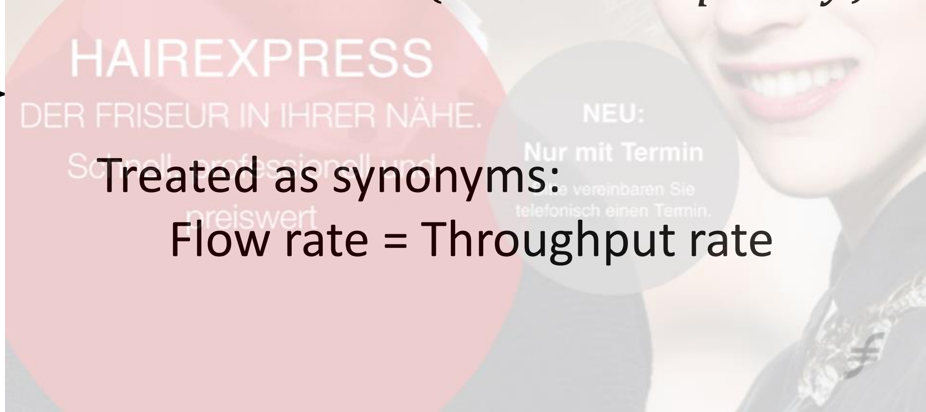


Hairdressing

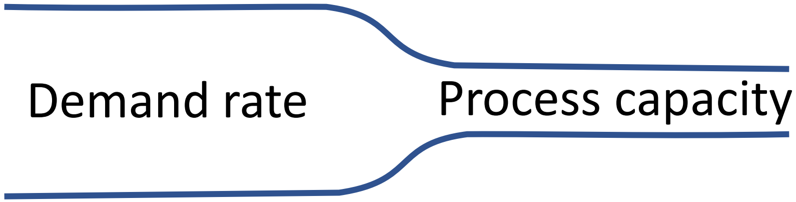
$$Flow\ rate = min\begin{Bmatrix} Demand\ rate, \\ Process\ capacity \end{Bmatrix}$$

Treated as synonyms:

Flow rate = Throughput rate

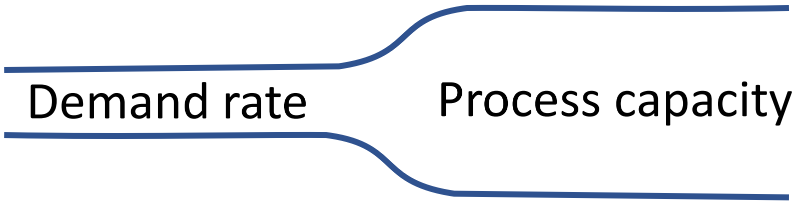


# Two Types of Constraints




Capacity-constrained:

Flow rate is limited by process capacity




Demand-constrained:

Flow rate is limited by demand rate

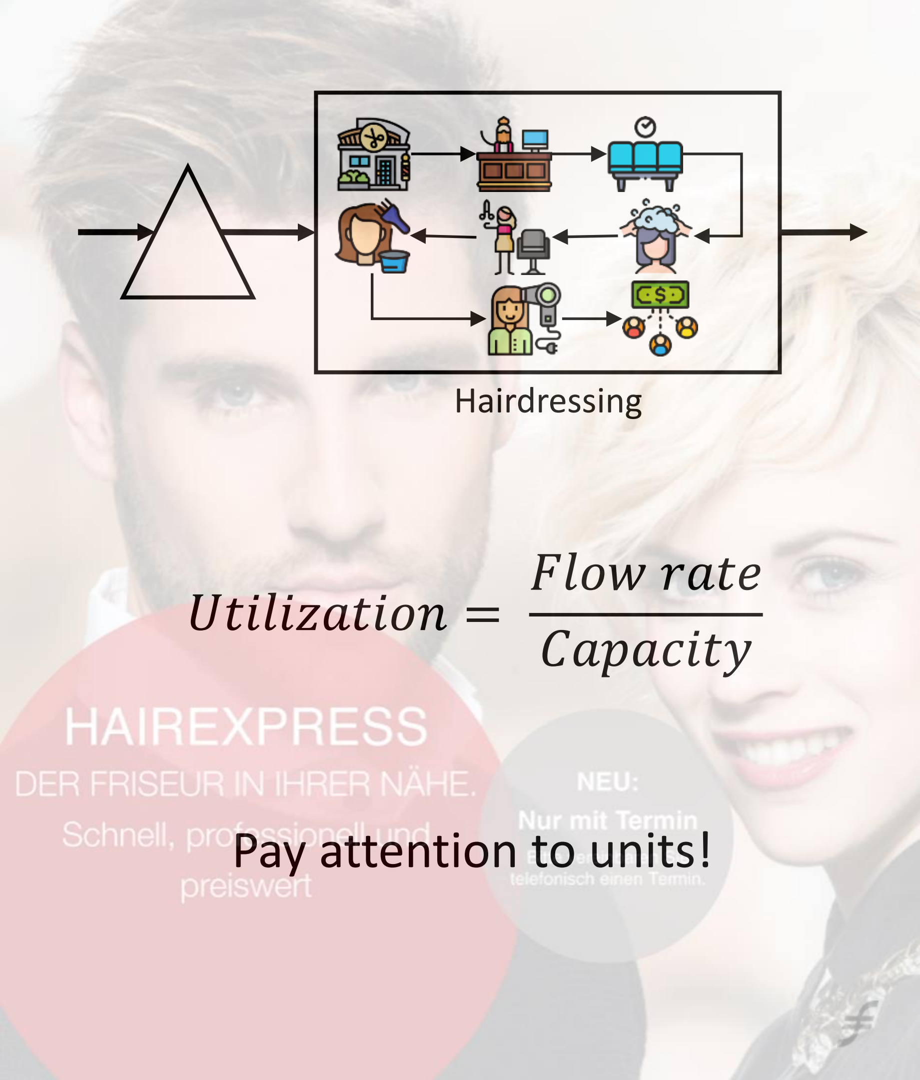
# Utilization

$$Flow\ rate = 1.1009\,\frac{customers}{hour}$$

$$Process\ capacity = 1.1009\,\frac{customers}{hour}$$

$$Utilization = \frac{1.1009\,\frac{customers}{hour}}{1.1009\,\frac{customers}{hour}}$$

$$= 1.0000 = 100\%$$




Hairdressing

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

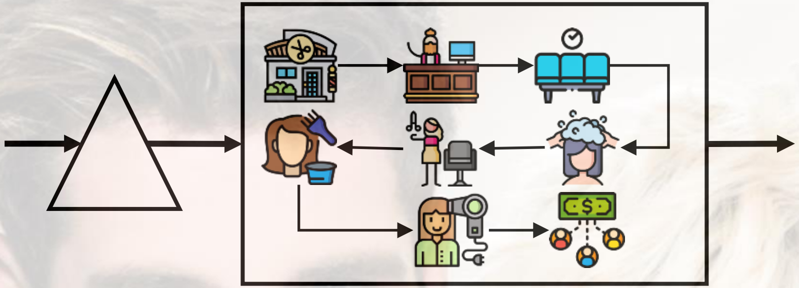
Pay attention to units!

# Implied Utilization

$$Demand\ rate = 12\,\frac{customers}{hour}$$

$$Process\ capacity = 1.1009\,\frac{customers}{hour}$$

$$\begin{array}{c} Implied \\ utilization \end{array} = \frac{12\,\frac{customers}{hour}}{1.1009\,\frac{customers}{hour}} = 10.9$$



Hairdressing

$$\begin{array}{c} Implied \\ utilization \end{array} = \frac{Demand\ rate}{Capacity}$$

Pay attention to units!

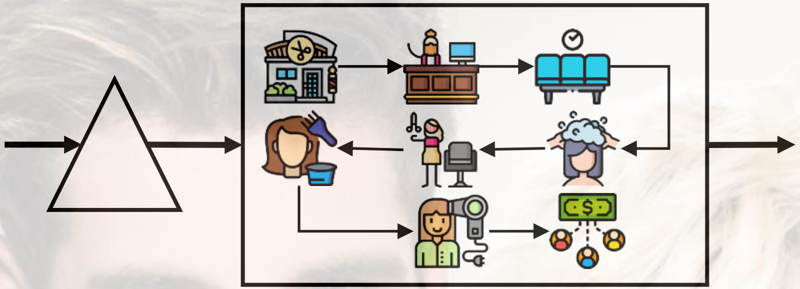
# Cycle Time

$$Flow\ rate = 1.1009\,\frac{customers}{hour}$$

$$Cycle\ time = \frac{1}{1.1009\,\frac{customers}{hour}}$$

$$= 0.9083\,\frac{hours}{customer}$$

$$= 54.5000\,\frac{min}{customer}$$



Hairdressing

$$Cycle\ time = \frac{1}{Flow\ Rate}$$

$$Cycle\ time = \frac{T}{I}$$

?

Cycle time = Processing time

Only when the system is capacity-constrained

# Definition of terms

- Processing time: Time use of resources on flow units
- Flow time: Ø Time span between process start and end
- Cycle time: Ø Time span (per flow unit) between the output of two flow units
- Process capacity: Maximum flow rate through a process


$$Processing\ time = 54.50\,\frac{hairdresser \cdot min}{customer}$$

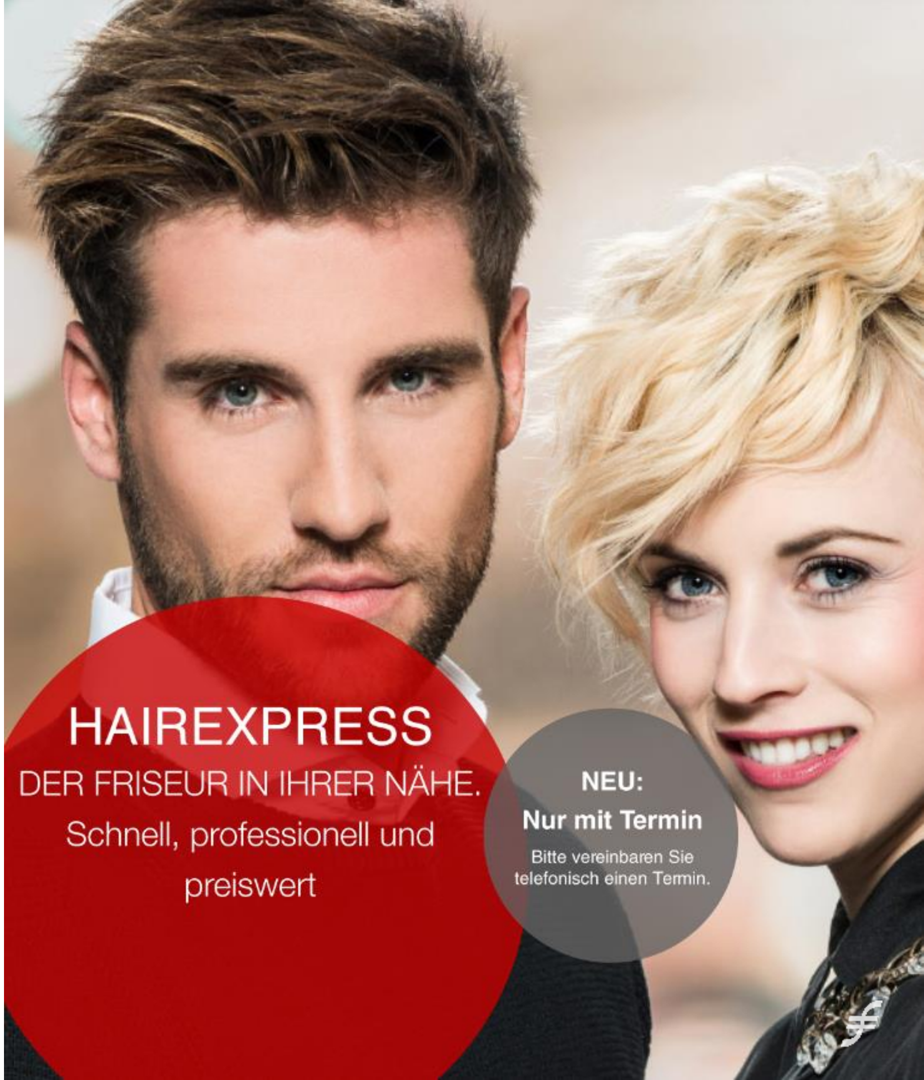
$$Flow\ time = 54.50\ min$$

$$Cycle\ time = 54.50\,\frac{min}{customer}$$

$$Process\ capacity = 1.1009\,\frac{customers}{hour}$$

# HAIREXPRESS
# Challenges

- What is the capacity of parallel one-step processes?
- How many resources (workstations) are needed to match demand ?



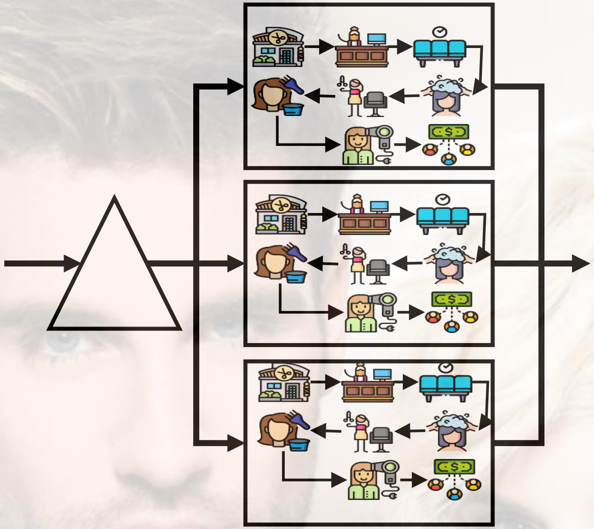
# Parallel Service Multiple Resources

$$Capacity = \frac{3}{54.5\,\frac{min}{customer}}$$

$$Capacity = 0.0550\,\frac{customers}{min}$$

$$= 0.0550\,\frac{customers}{min} \cdot 60\,\frac{min}{hour}$$

$$= 3.3028\,\frac{customers}{hour}$$



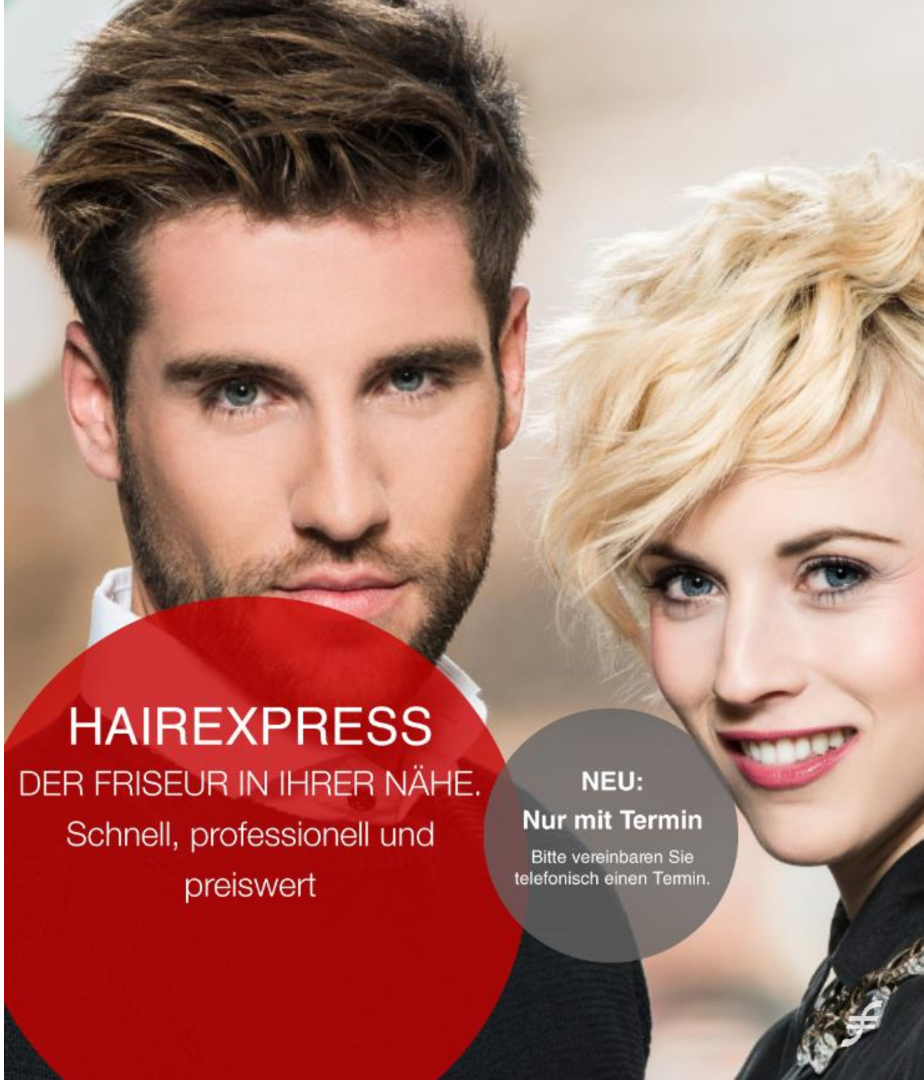
One-Step process with
3 parallel resources

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

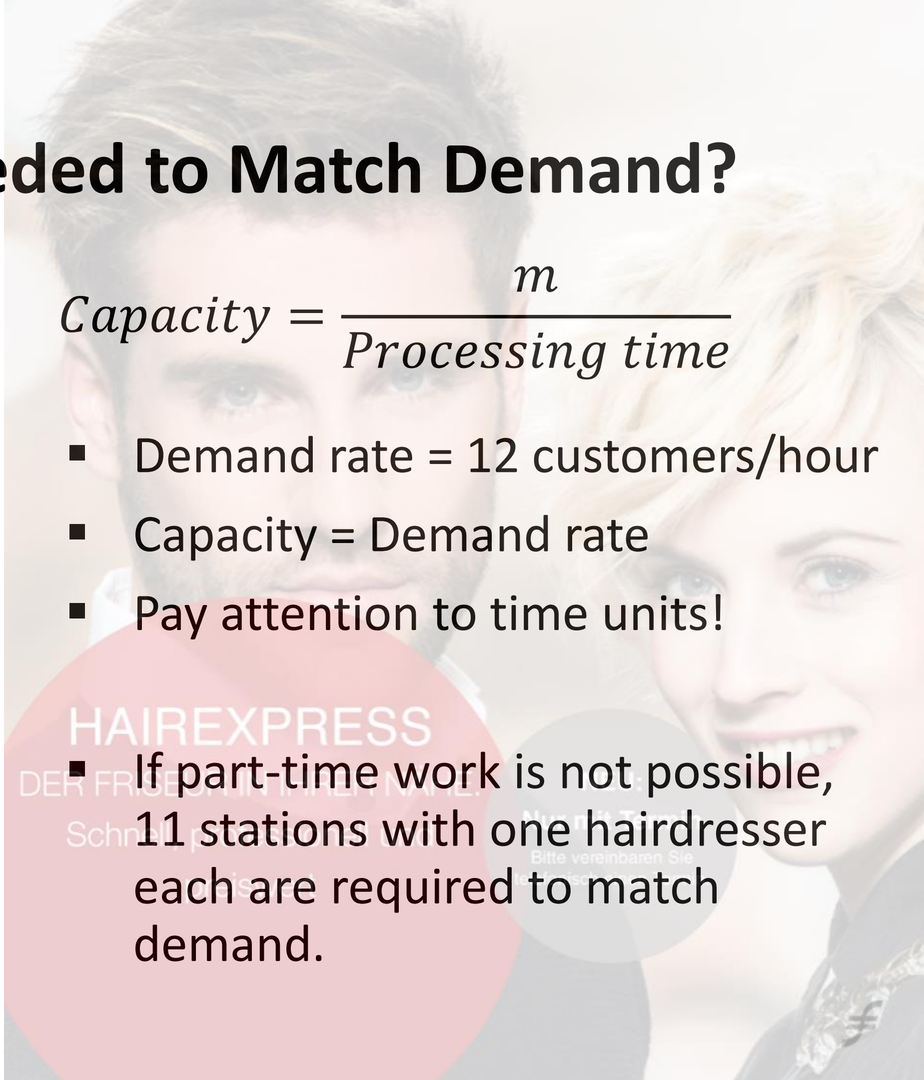
m: number of units processed in parallel
= number of resources available in parallel

# HAIREXPRESS Challenges

- What is the capacity of parallel one-step processes?
- **How many resources (workstations) are needed to match demand ?**



# How Many Workstations Needed to Match Demand?




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

- Demand rate = 12 customers/hour
- Capacity = Demand rate
- Pay attention to time units!

$$\frac{12\,\frac{customers}{hour}}{60\,\frac{min}{hour}} = \frac{m}{54.5\,\frac{hairdresser \cdot min}{customer}}$$

$$m = \frac{12\,\frac{customers}{hour}}{60\,\frac{min}{hour}} \cdot 54.5\,\frac{hairdresser \cdot min}{customer}$$

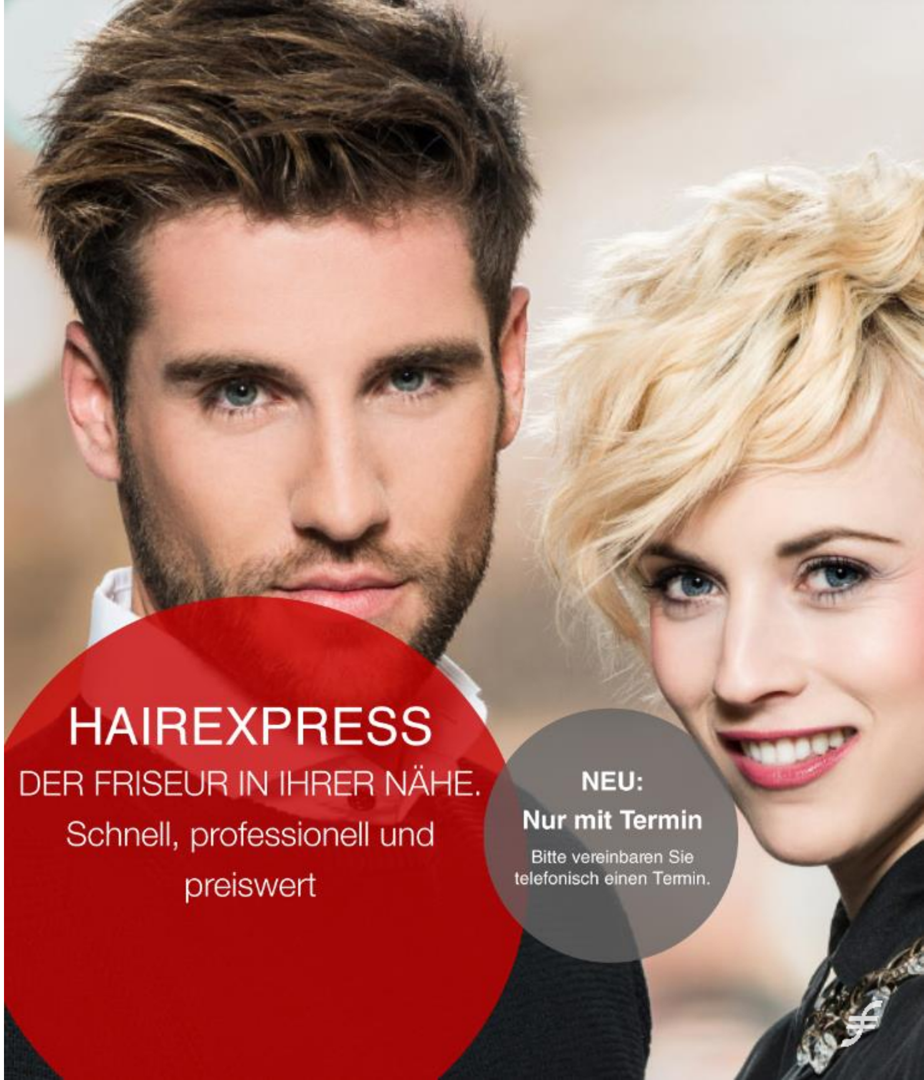
$$m = 10.9\ hairdresser$$

- If part-time work is not possible, 11 stations with one hairdresser each are required to match demand.

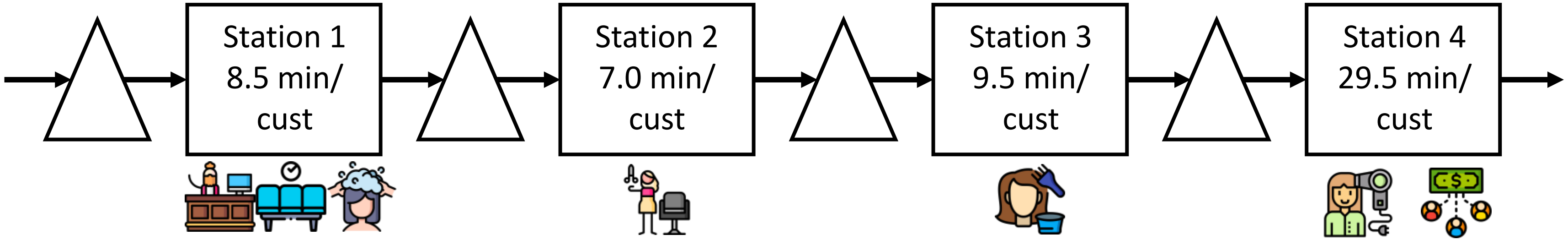
# MULTISTEP PROCESS

# HAIREXPRESS
# Challenges

- How to determine the capacity of a multistep process?
- Where is the bottleneck in a multistep process?
- How to determine utilization and flow rate in a multistep process?
- How long does it take to serve a certain number of customers with a multistep process?



# Analysis of a Multistep Process (multiple resources)




$Capacity$

$$\frac{1}{8.5\,\frac{min}{customer}} = 0.1176\,\frac{customers}{min} = 7.06\,\frac{customers}{hour}$$

$$\frac{1}{7.0\,\frac{min}{customer}} = 0.1429\,\frac{customers}{min} = 8.57\,\frac{customers}{hour}$$

$$\frac{1}{9.5\,\frac{min}{customer}} = 0.1053\,\frac{customers}{min} = 6.32\,\frac{customers}{hour}$$

$$\frac{1}{29.5\,\frac{min}{customer}} = 0.0339\,\frac{customers}{min} = 2.03\,\frac{customers}{hour}$$

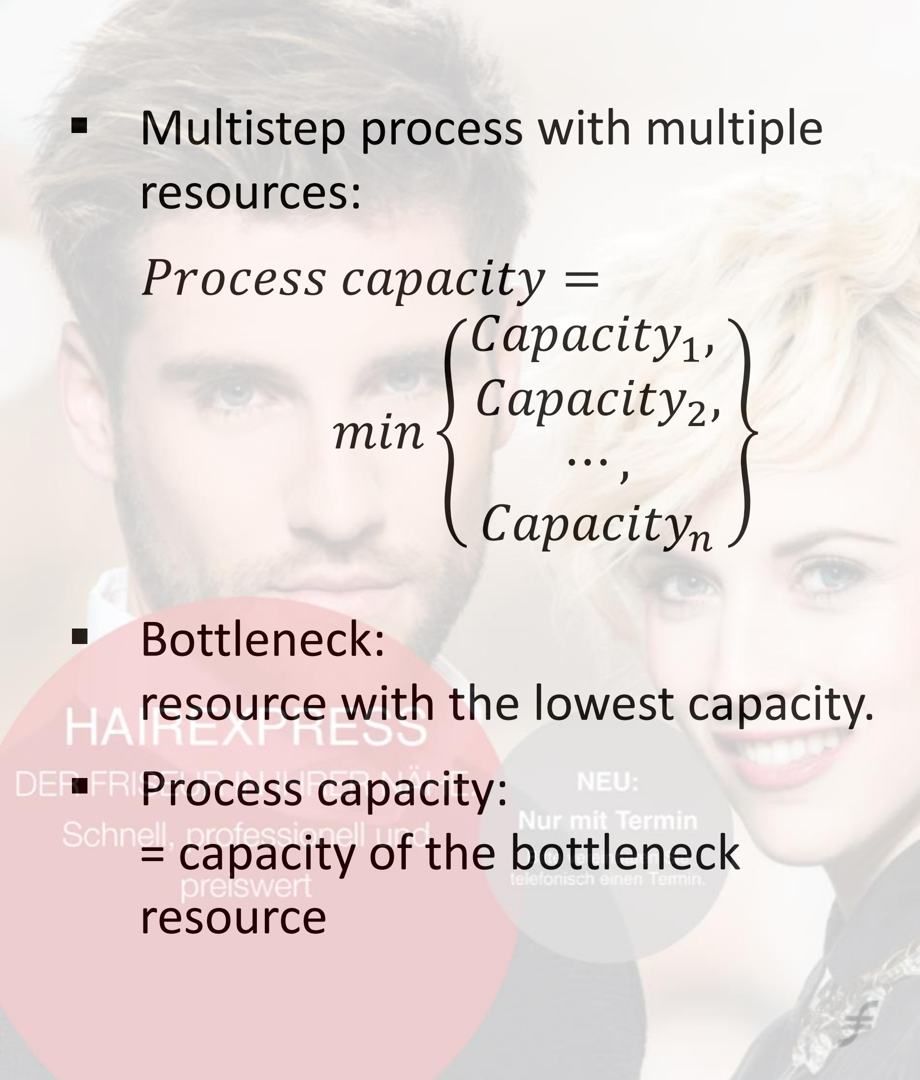
# Process Capacity & Bottleneck

$$Process\ capacity$$

$$= \min\left\{\begin{matrix} 7.06\,\dfrac{customers}{hour}, 8.57\,\dfrac{customers}{hour}, \\ 6.32\,\dfrac{customers}{hour}, 2.03\,\dfrac{customers}{hour} \end{matrix}\right\}$$

$$= 2.03\,\frac{customers}{hour}$$

Bottleneck is station 4.



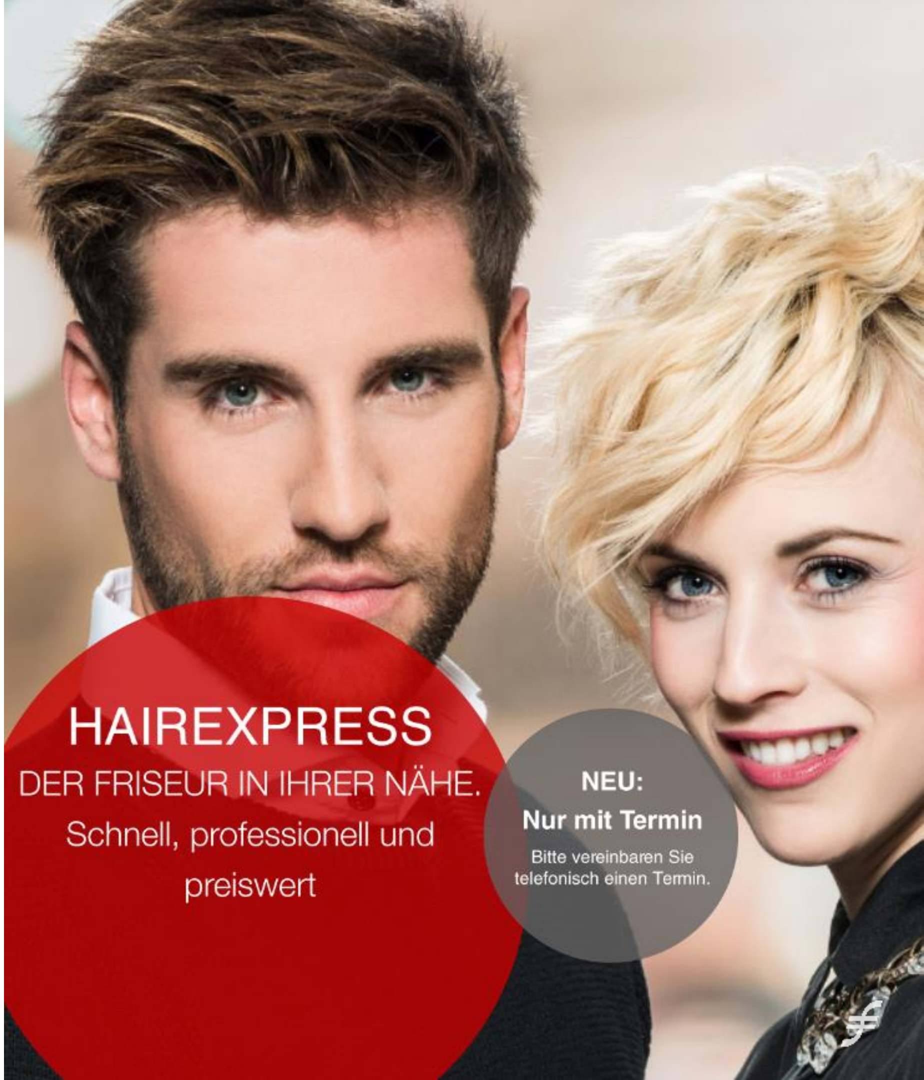

- Multistep process with multiple resources:

$$Process\ capacity = \min\left\{\begin{matrix} Capacity_1, \\ Capacity_2, \\ \dots, \\ Capacity_n \end{matrix}\right\}$$

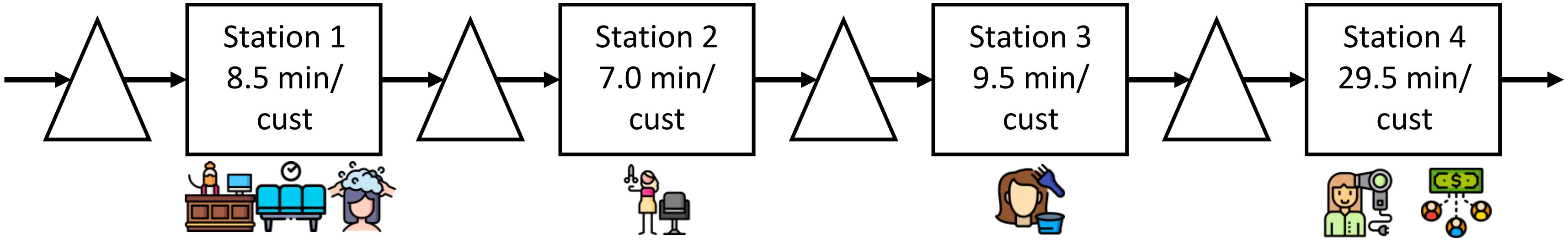
- Bottleneck:
  resource with the lowest capacity.
- Process capacity:
  = capacity of the bottleneck resource

# HAIREXPRESS
# Challenges

- How to determine the capacity of a multistep process?
- Where is the bottleneck in a multistep process?
- **How to determine utilization and flow rate in a multistep process?**
- How long does it take to serve a certain number of customers with a multistep process?



# Flow Rate and Utilization



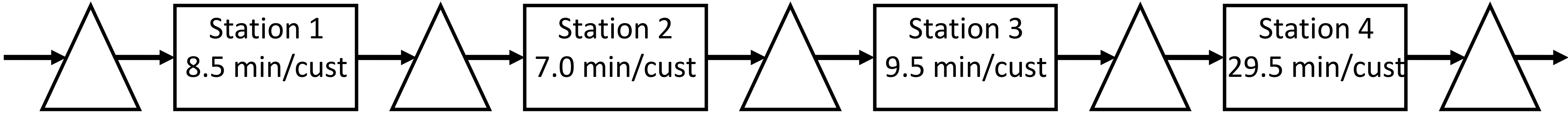

$$Capacity = 7.06\,\frac{customers}{hour} \qquad = 8.57\,\frac{customers}{hour} \qquad = 6.32\,\frac{customers}{hour} \qquad = 2.03\,\frac{customers}{hour}$$

$$Demand = 12\,\frac{customers}{hour} \qquad Flow\ rate = \min\left(12\,\frac{customers}{hour}, 2.03\,\frac{customers}{hour}\right)$$

$$Utilization = 0.2876 \qquad = 0.2368 \qquad = 0.3214 \qquad = 1.0000$$

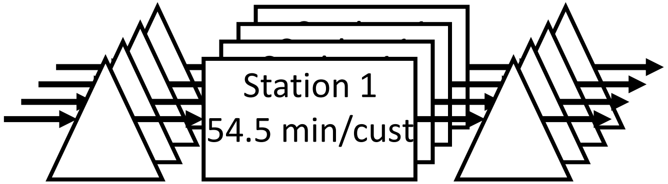
$$Demand = 12\,\frac{customers}{hour}$$

# Downside of Specialization




$$Average\ utilization = \frac{0.2876 + 0.2368 + 0.3214 + 1}{4} = 0.4610$$

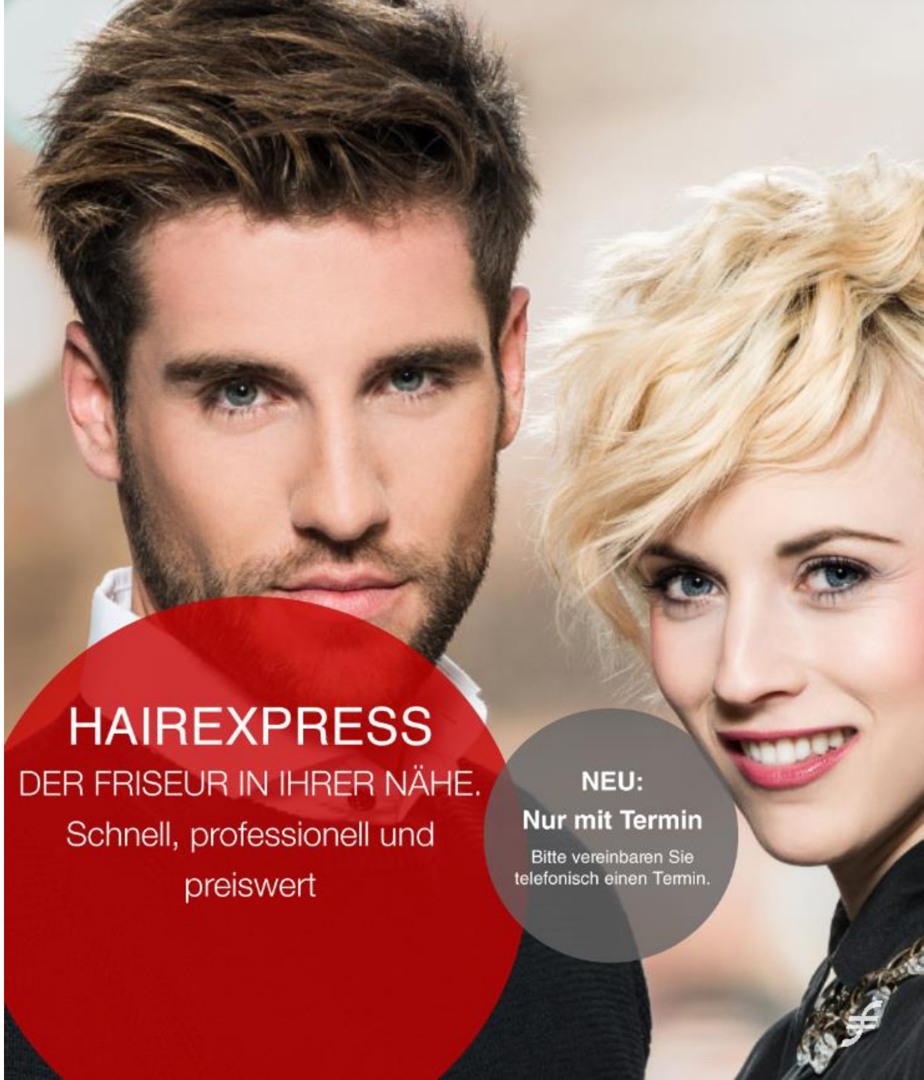
Parallel process:




$$Average\ utilization =$$

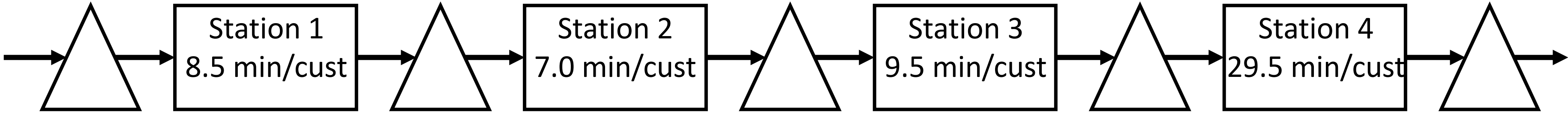
# HAIREXPRESS
# Challenges

- How to determine the capacity of a multistep process?
- Where is the bottleneck in a multistep process?
- How to determine utilization and flow rate in a multistep process?
- **How long does it take to serve a certain number of customers with a multistep process?**



# Serial vs Parallel Process (Working)

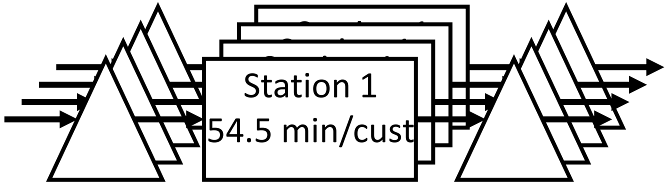
Serial process with specialists




Cycle time = processing time at the bottleneck = 29.5 min/customer

$$Time\ to\ serve\ 10\ customers = 29.5\,\frac{min}{customer} \cdot 10\ customers = 295\,min$$

Parallel process with generalists (manufacturing cell)



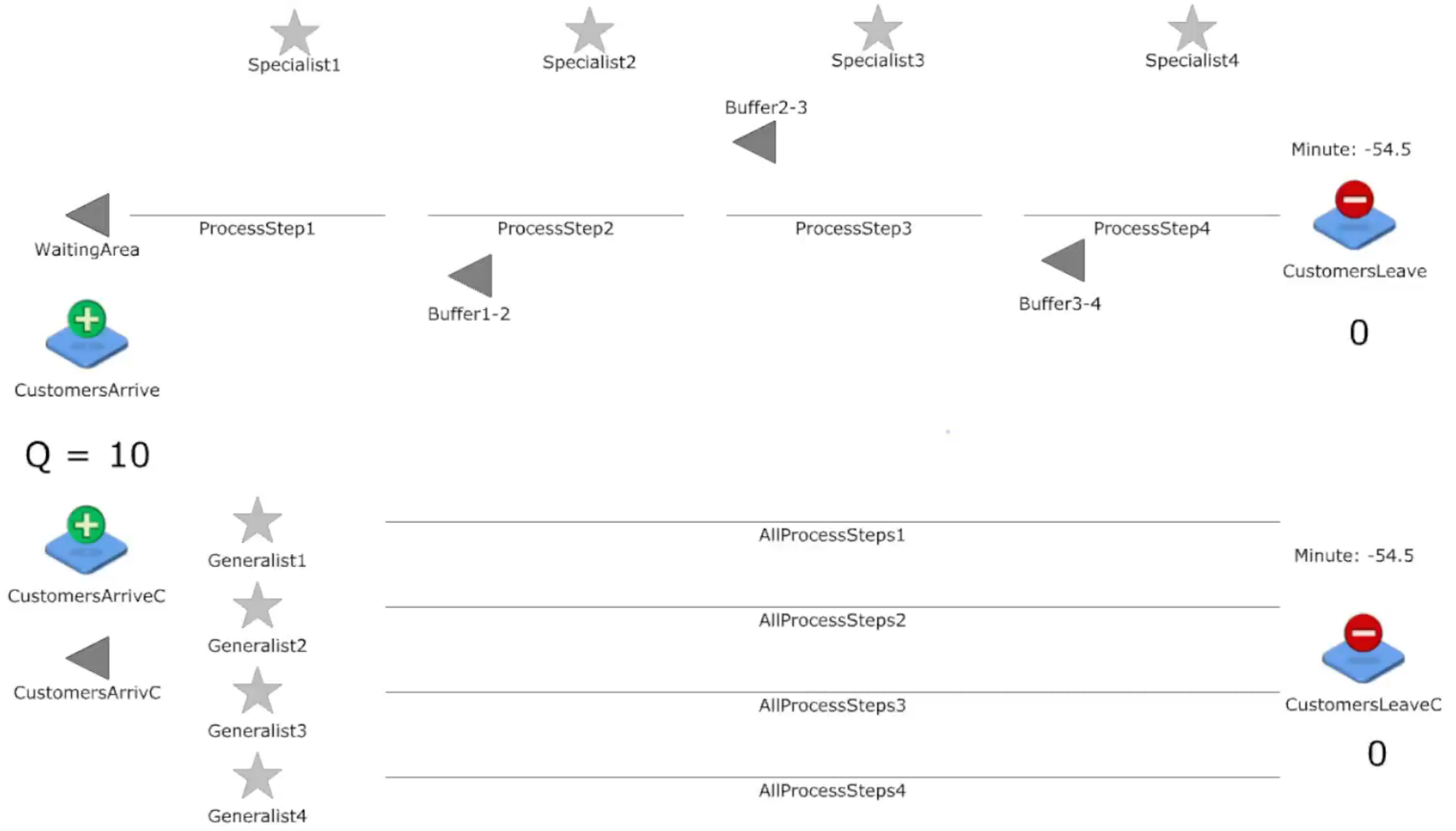

$$Cycle\ time = 1 \Big/ \frac{4\ stations}{54.5\,\frac{station \cdot min}{customer}} = 13.625\,\frac{min}{customer}$$

$$Time\ to\ serve\ 10\ customers = 13.625\,\frac{min}{customer} \cdot 10\ customers = 136.25\,min$$

## Serial versus Parallel Process - Searial Manufacturing versus Manufacturing Cell

Time to serve Q customers when operating

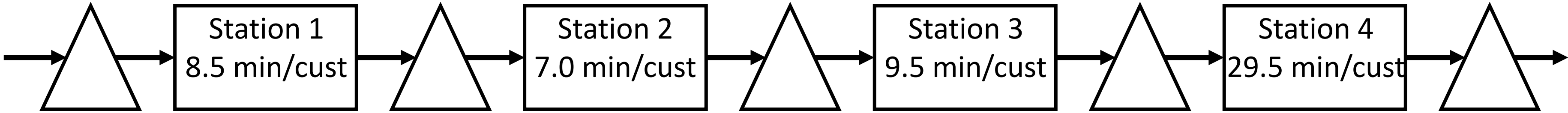
00:00:00



# Serial Process without Takt with Buffers (Starts Empty)

Serial production (without takt):

- serial system with buffers between the stations
- no automated transport of flow units




$$Time\ to\ serve\ first\ customer = 8.5\ m + 7.0\ m + 9.5\ m + 29.5\ m = 54.5\ min$$

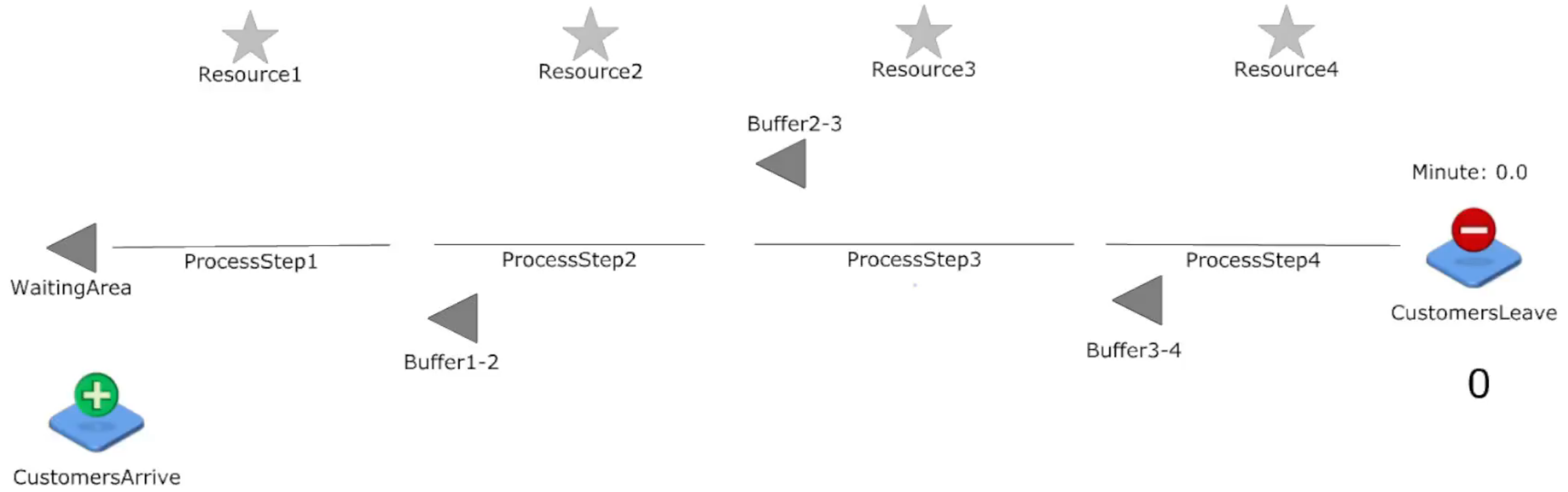
$$Time\ to\ serve\ 9\ more\ customers = 29.5\ \frac{min}{customer} \cdot 9\ customers = 265.5\ min$$

$$Time\ to\ serve\ 10\ customers = 265.5\ min + 54.5\ min = 320\ min$$

# Serial Worker Paced Process with Buffers (Empty)

Time to serve Q customers

00:00:00

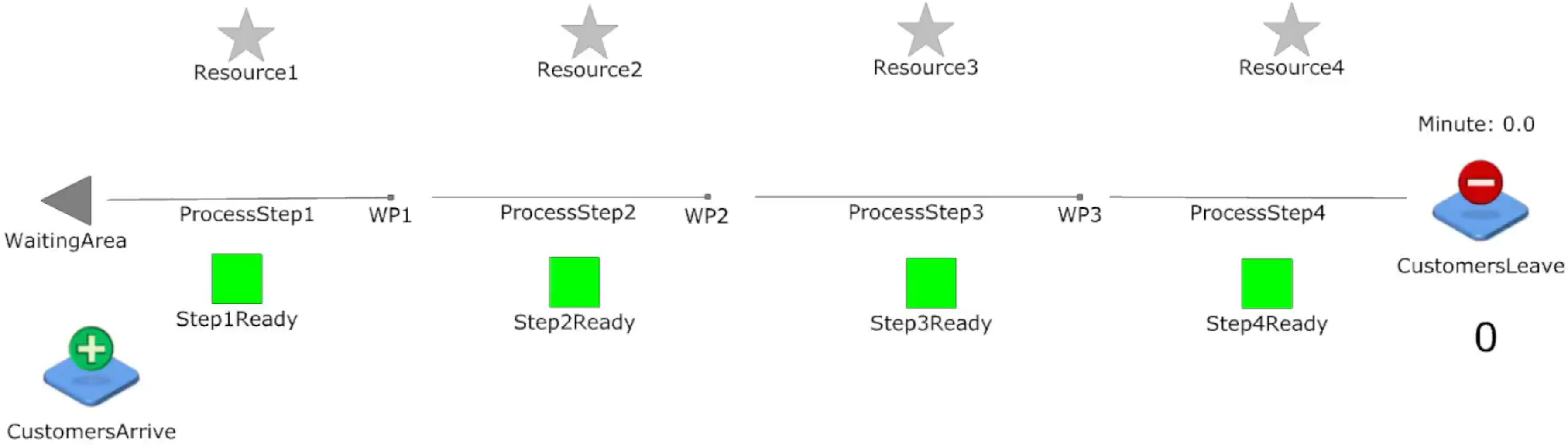



Q = 10

# Serial Worker Paced Process without Buffers (Empty)

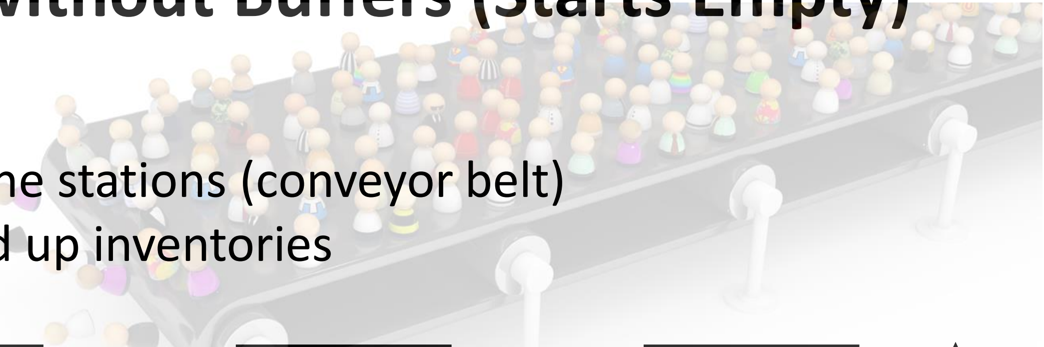
Time to serve Q customers

00:00:00




Q = 10

# Serial Process with Takt without Buffers (Starts Empty)



Serial production (with takt):

- automated transport between the stations (conveyor belt)
- no buffers, no possibility to build up inventories


$$Time\ to\ serve\ first\ customer = 29.5\,m + 29.5\,m + 29.5\,m + 29.5\,m = 118\,min$$

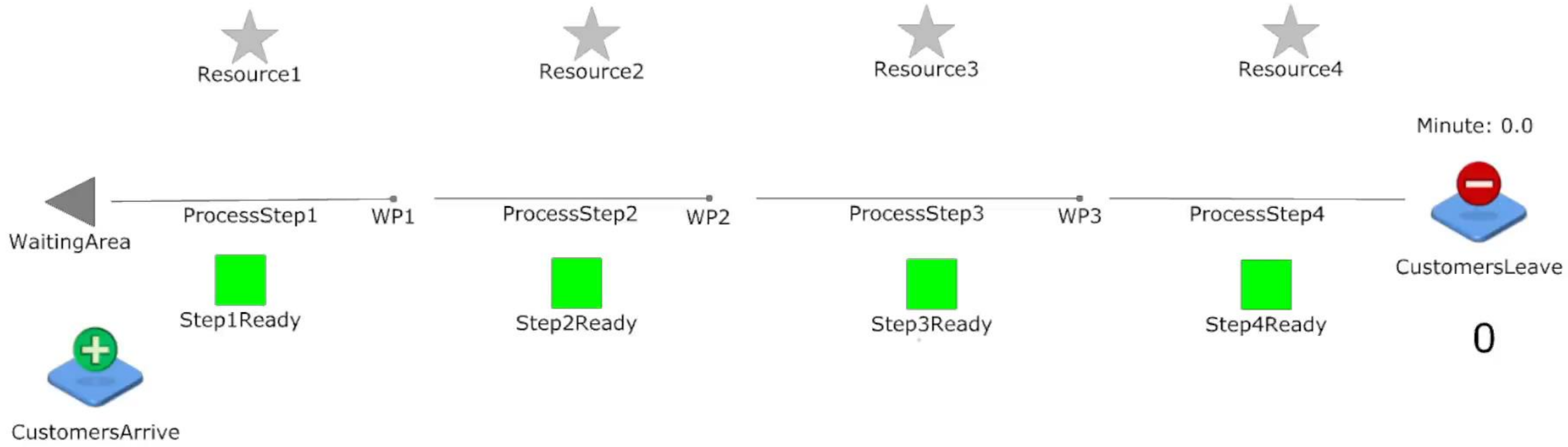
$$Time\ to\ serve\ 9\ more\ customers = 29.5\frac{min}{customer} \cdot 9\ customers = 265.5\,min$$

$$Time\ to\ serve\ 10\ customers = 265.5\,min + 118\,min = 383.5\,min$$

# Serial Machine Paced Process without Buffers (Empty)

Time to serve Q customers

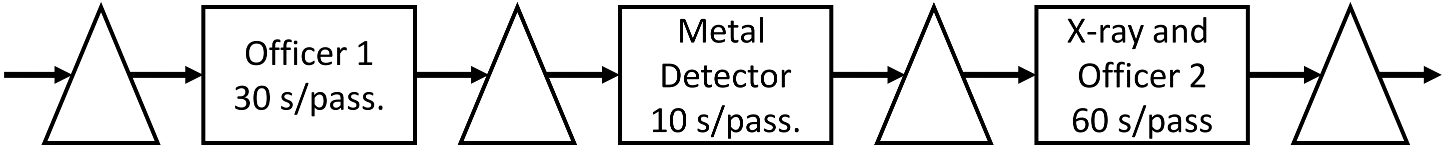
00:00:00




Q = 10 Takt time = 29.5 min

# BACKUP

# How long does it take to serve a group of 40?




The process is empty at 6:00 when a group of 40 passengers arrive.

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# 2023
# Operations Management

# PROCESS IMPROVEMENT

# Xootr LLC

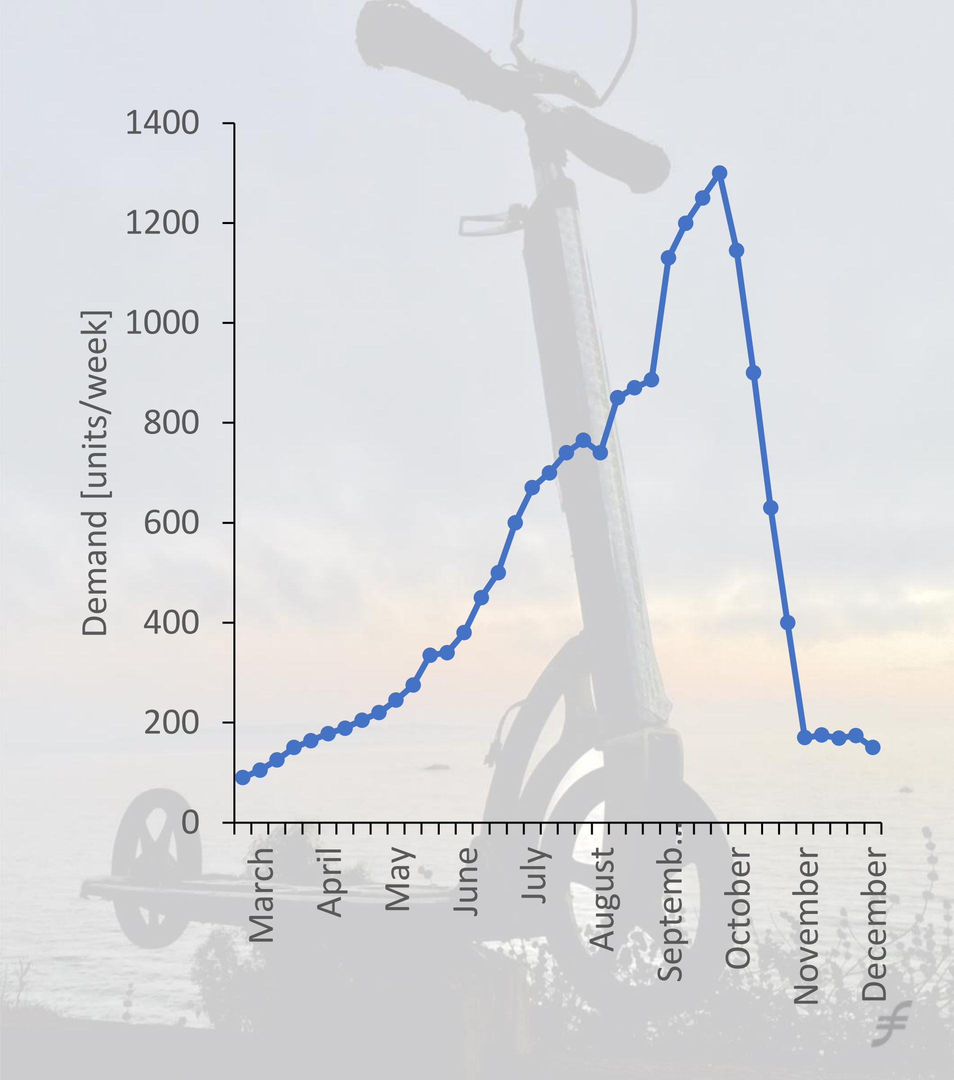
- Roots of Xootr go back to 1999, when Nova Cruz Products was founded.
- 2003 the Nova Cruz was sold, but founders were able to buy the original kick-scooter business back.
- New company has grown profitably ever since its formation.



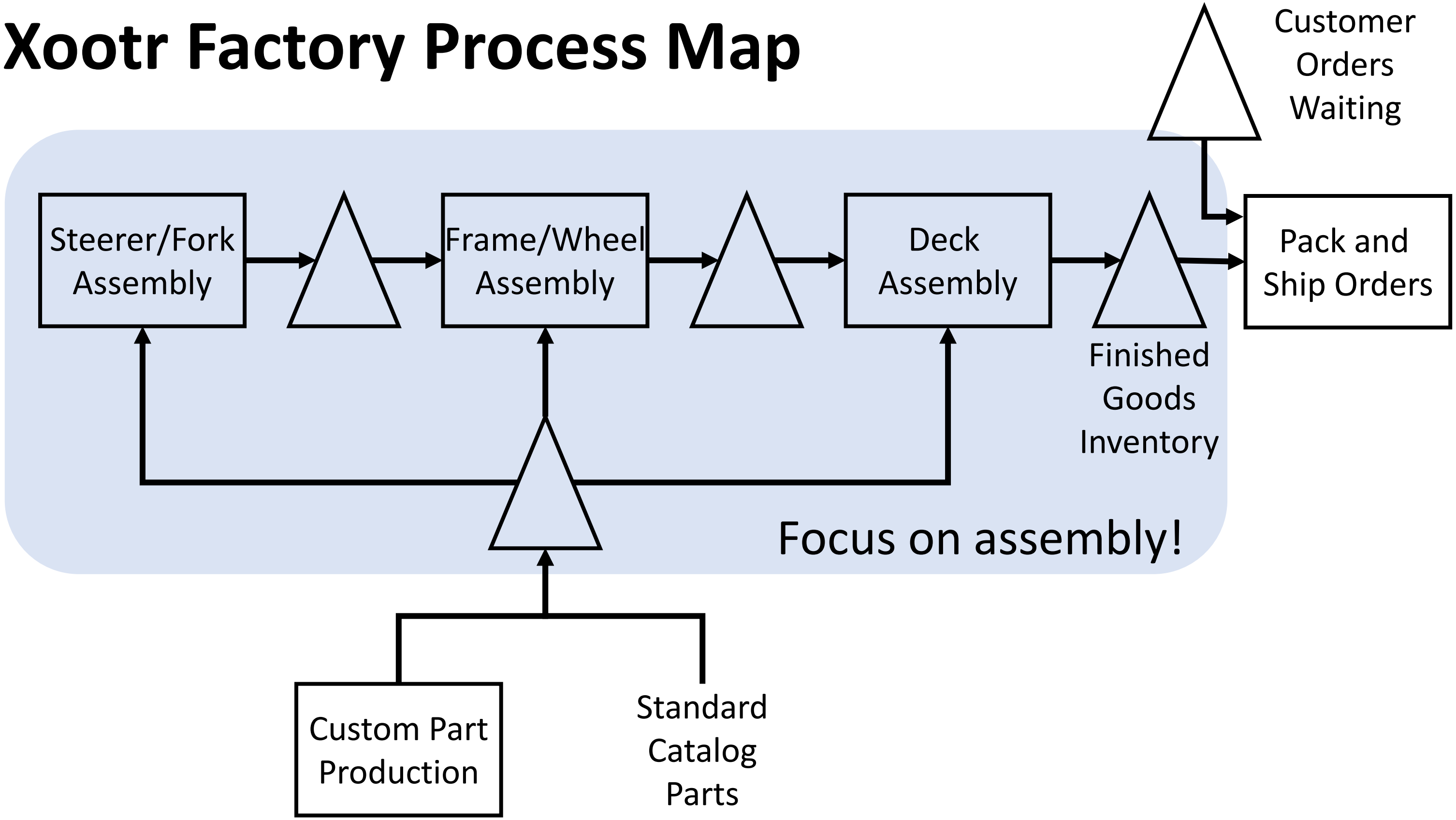
https://www.xootr.com/

# Xootr Challenges

- How to measure process efficiency?
- How to improve process efficiency?
- How to scale up production?



# Xootr Factory Process Map

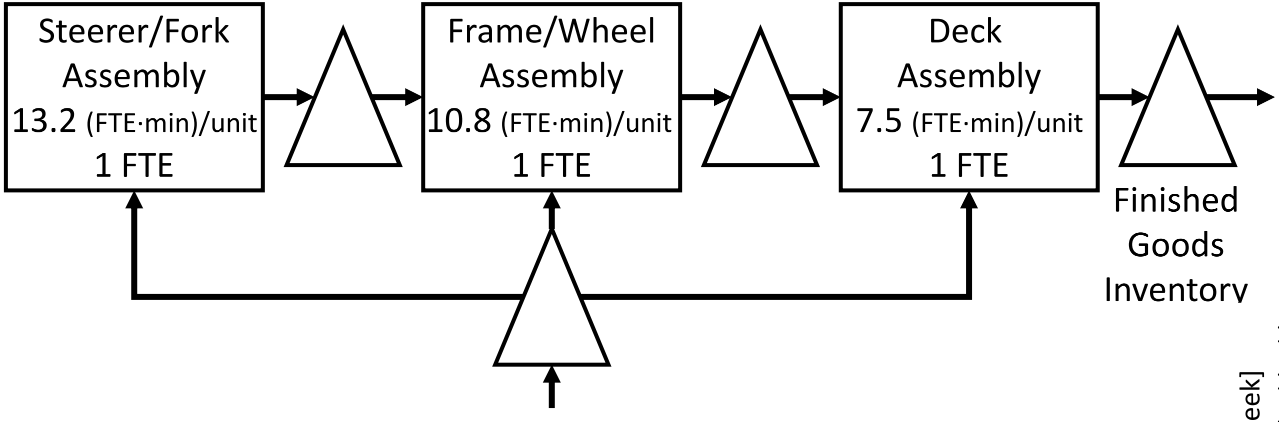



https://www.xootr.com/factoryTour/factoryTour.htm

# Process Efficiency

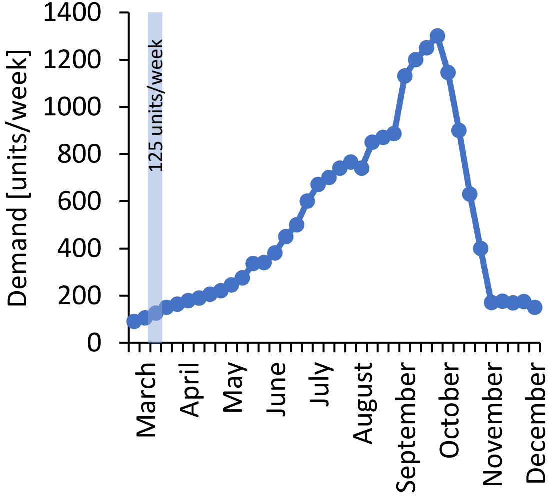
- “A process is efficient if it is able to achieve a high flow rate with few resources.”
- Focus on resources necessary, for example deck assembly processing requires
  - 1 worker (FTE = full time equivalent) for 8 minutes per unit.
  - 1 drilling machine for 3 minutes per unit.
  - …
- Typical measures of labor efficiency
  - Cost of direct labor
  - Average labor utilization
  - Idle time

# Production Situation in March




Demand rate: 125 units/week
Process capacity: 159.0909 units/week
Worker work time: 35 hours/week
Workers get paid 12 € per hour, also if they are idle.

How good is labor efficiency in March?



# Cost of Direct Labor

$$Flow\ rate = 125\,\frac{units}{week}$$

$$Total\ wages$$
$$= 3\ FTE \cdot 12\,\frac{€}{hour \cdot FTE} \cdot 35\,\frac{hour}{week}$$
$$= 1{,}260\,\frac{€}{week}$$

$$\begin{matrix}Cost\ of\\ direct\ labor\end{matrix} = \frac{1{,}260\,\frac{€}{week}}{125\,\frac{units}{week}} = 10.08\,\frac{€}{Unit}$$

$$\begin{matrix}Cost\ of\\ direct\ labor\end{matrix} = \frac{Total\ wages}{Flow\ rate}$$

Wages and flow rate must be measured in same units of time!

# Average Labor Utilization

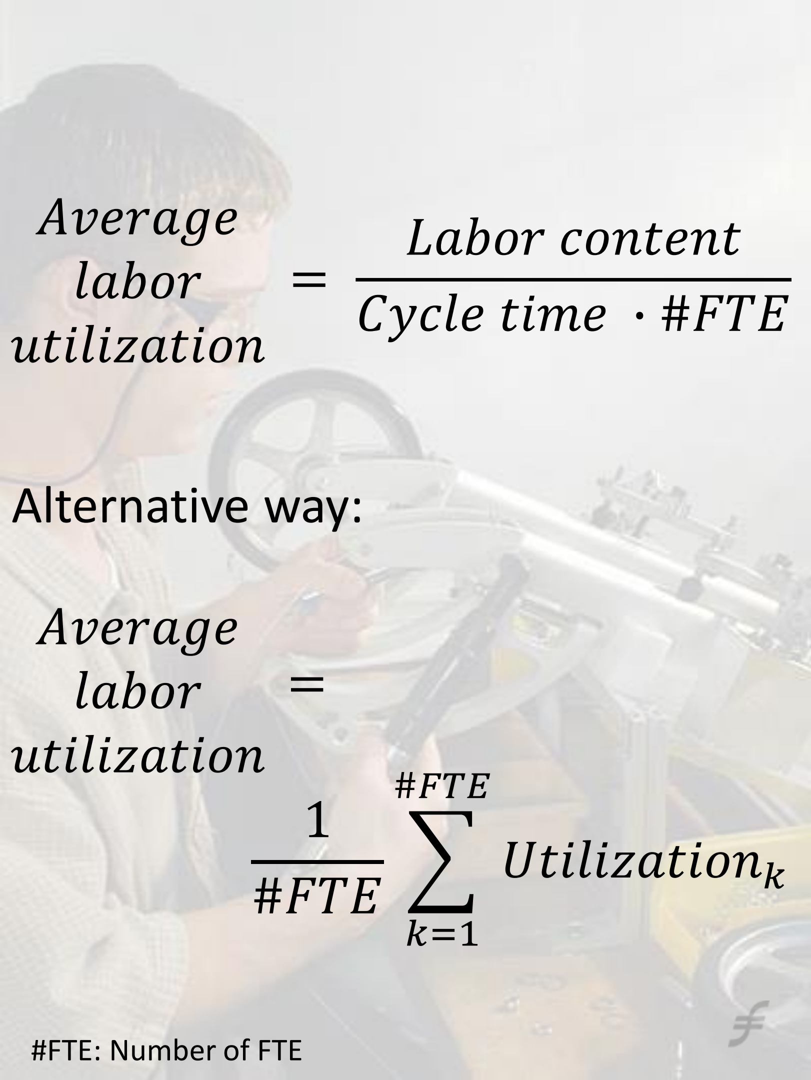
$$Labor\ content =$$

$$13.2 + 10.8 + 7.5 = 31.5 \left[\frac{FTE \cdot min}{unit}\right]$$

$$Cycle\ time = \frac{1}{125\,\frac{units}{week}} \cdot 35\,\frac{hour}{week} \cdot 60\,\frac{min}{hour}$$

$$Cycle\ time = 16.8\,\frac{min}{unit}$$

$$\begin{matrix} Average \\ labor \\ utilization \end{matrix} = \frac{31.5\,\frac{FTE \cdot min}{unit}}{16.8\,\frac{min}{unit} \cdot 3FTE} = 0.6250$$



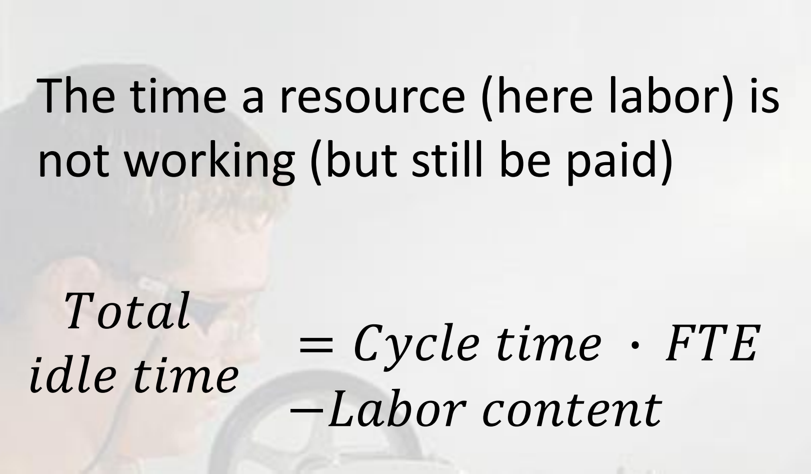
$$\begin{matrix} Average \\ labor \\ utilization \end{matrix} = \frac{Labor\ content}{Cycle\ time\ \cdot \#FTE}$$

Alternative way:

$$\begin{matrix} Average \\ labor \\ utilization \end{matrix} = \frac{1}{\#FTE} \sum_{k=1}^{\#FTE} Utilization_k$$

#FTE: Number of FTE

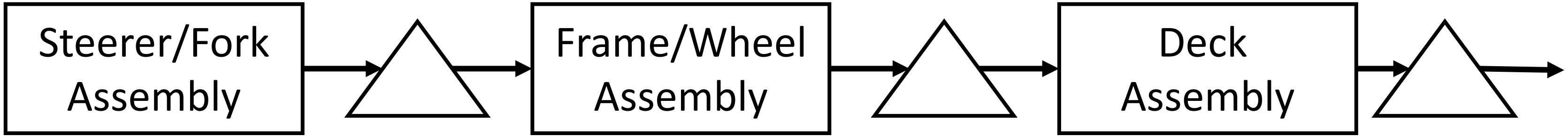
# Idle Time



The time a resource (here labor) is not working (but still be paid)

$$\begin{array}{c}Total\\ idle\ time\end{array} = Cycle\ time \cdot FTE - Labor\ content$$

$$\begin{array}{c}Total\\ idle\ time\end{array} = 16.8\frac{min}{unit} \cdot 3FTE - 31.5\frac{FTE \cdot min}{unit} = 18.9\frac{FTE \cdot min}{unit}$$



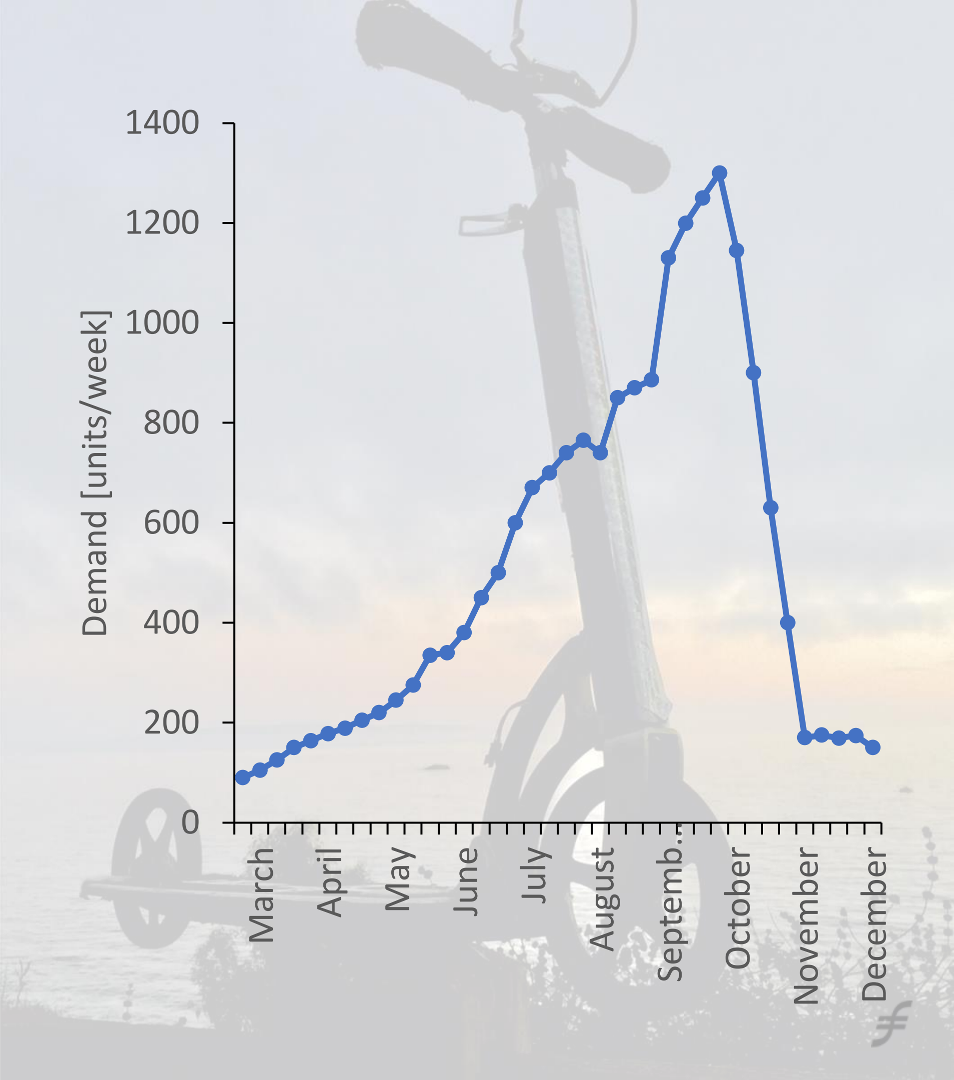

$$Idle\ time\ at\ each\ station =$$

$$3.6\frac{FTE \cdot min}{unit} \qquad 6.0\frac{FTE \cdot min}{unit} \qquad 9.3\frac{FTE \cdot min}{unit}$$

# Two Reasons For Idle Time

# Xootr Challenges

- How to measure process efficiency?
- **How to improve process efficiency?**
- How to scale up production?



# How to Improve Process Efficiency?

Increase demand!




Improve the process

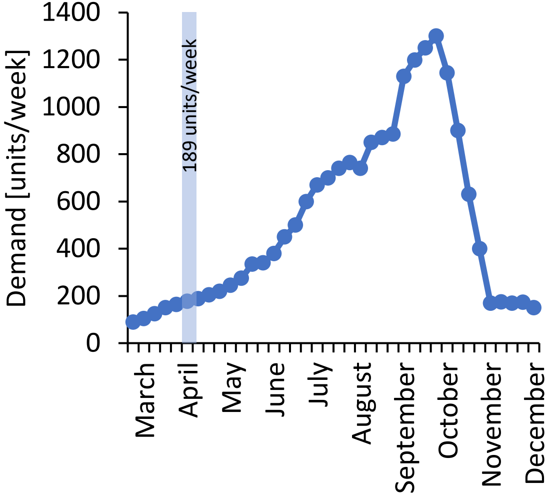
# Performance of a Capacity Constrained System

$$\begin{matrix}Cost\ of\\ direct\ labor\end{matrix} = \frac{1{,}260\,\frac{€}{week}}{159.0909\,\frac{units}{week}} = 7.92\,\frac{€}{Unit}$$

$$\begin{matrix}Total\\ idle\ time\end{matrix} = 13.2\,\frac{min}{unit}\cdot 3FTE - 31.5\,\frac{FTE\cdot min}{unit}$$

$$= 8.1\,\frac{FTE\cdot min}{unit}$$

$$\begin{matrix}Average\\ labor\\ utilization\end{matrix} = \frac{31.5\,\frac{FTE\cdot min}{unit}}{13.2\,\frac{min}{unit}\cdot 3FTE} = 0.7955$$

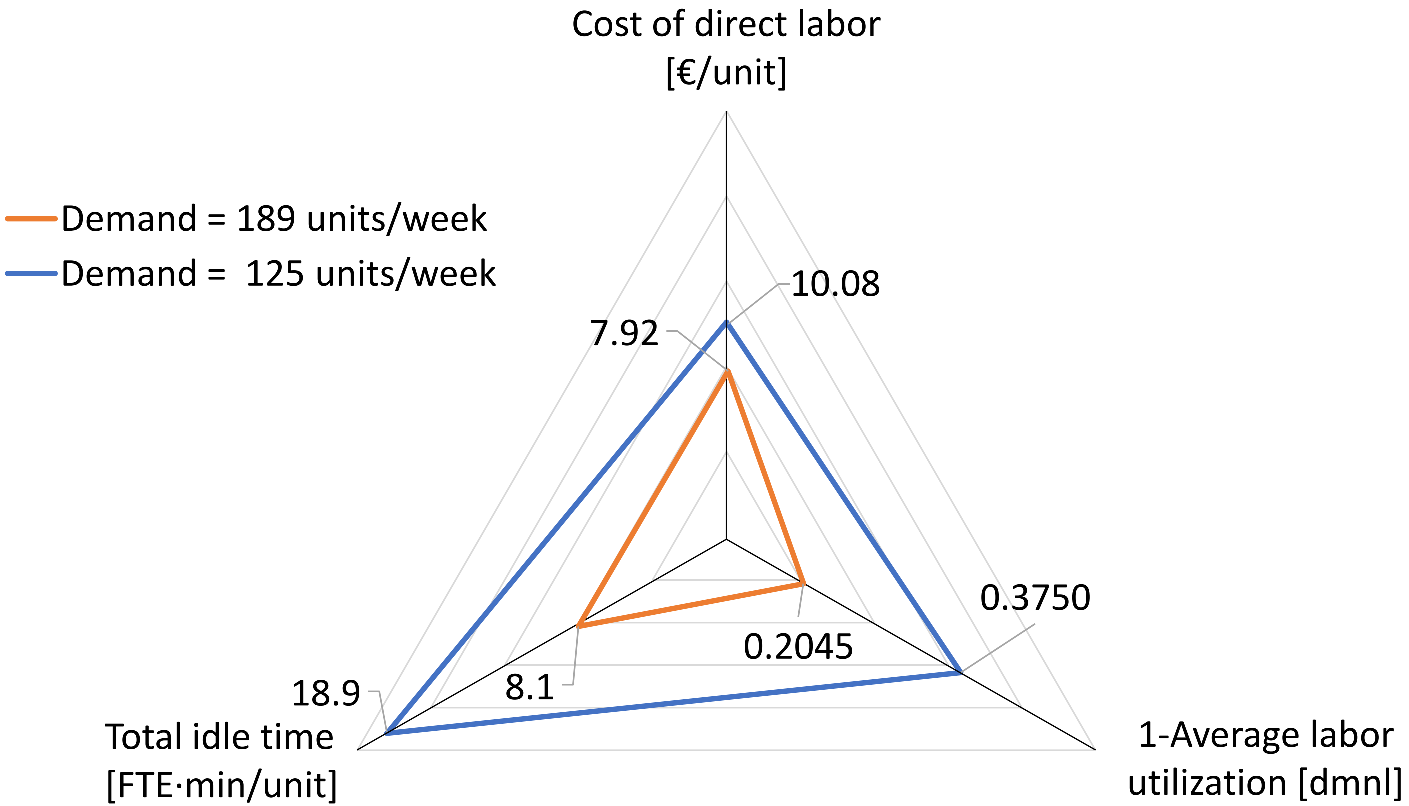



Demand rate: 189 units/week

Flow rate = Process capacity: 159.0909 units/week

Cycle time: 13.2 min/unit

# Relation of Labor Efficiency Measures



# How to Improve Process Efficiency?



Increase demand!


Improve the process

# How to Improve a Process?

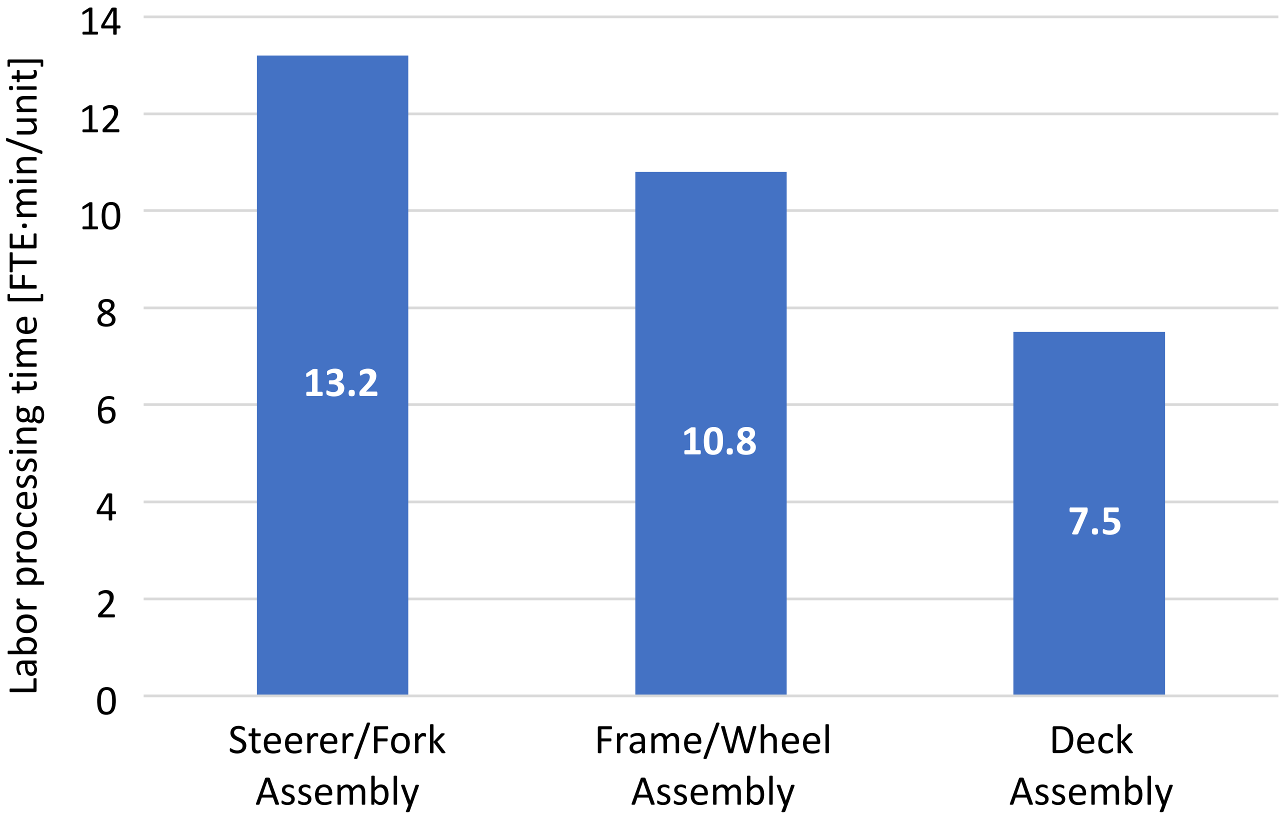
- Process improvement starts by looking at the bottleneck.
- Recap: bottleneck is a resource with the lowest capacity.
- Understanding the location of the bottleneck is critical for improving a process.

# Off-Loading the Bottleneck…

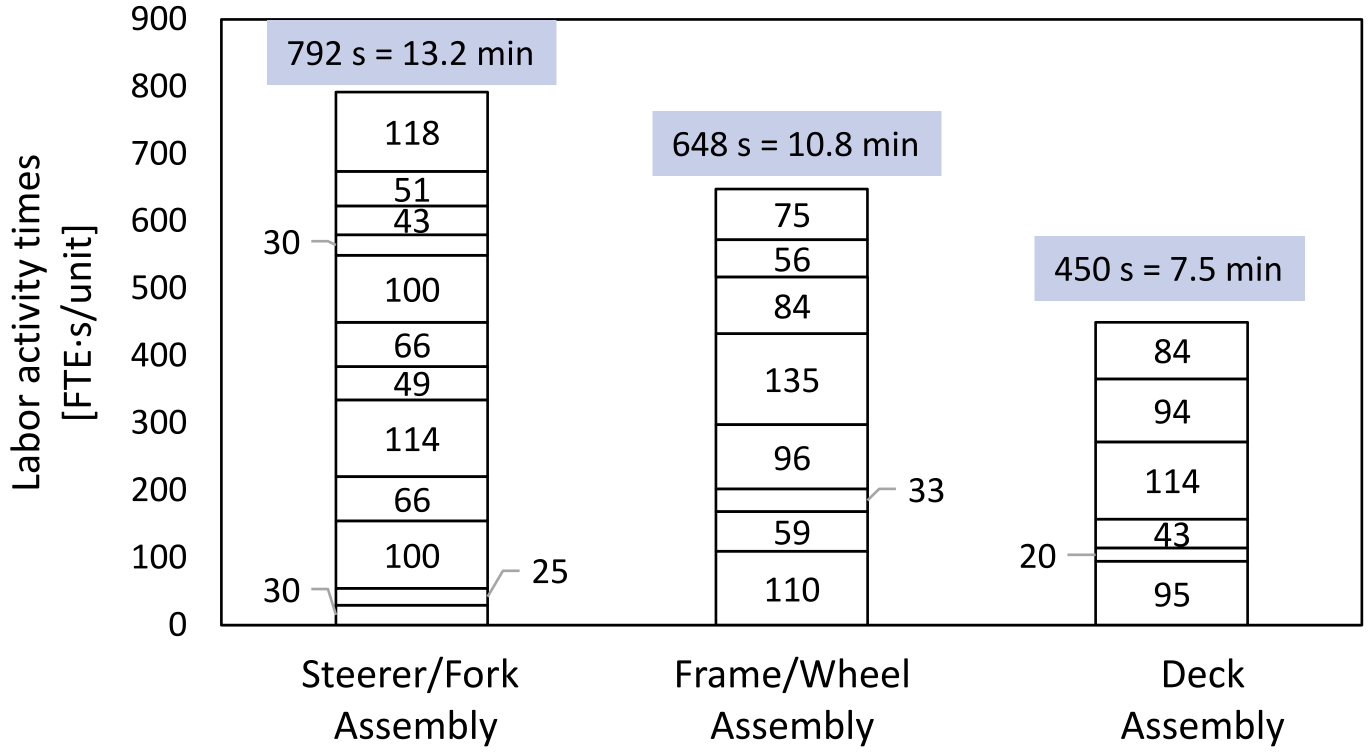
…by:

- line-balancing.
- automating some of the activities consuming time at the bottleneck by using technology.
- outsourcing some of the activities consuming time at the bottleneck.

# Imbalance in Labor Processing Times



# Line Balancing Requires a Micro-level Perspective



# How to Balance a Process

Line Balancing

for a fixed sequence of activities

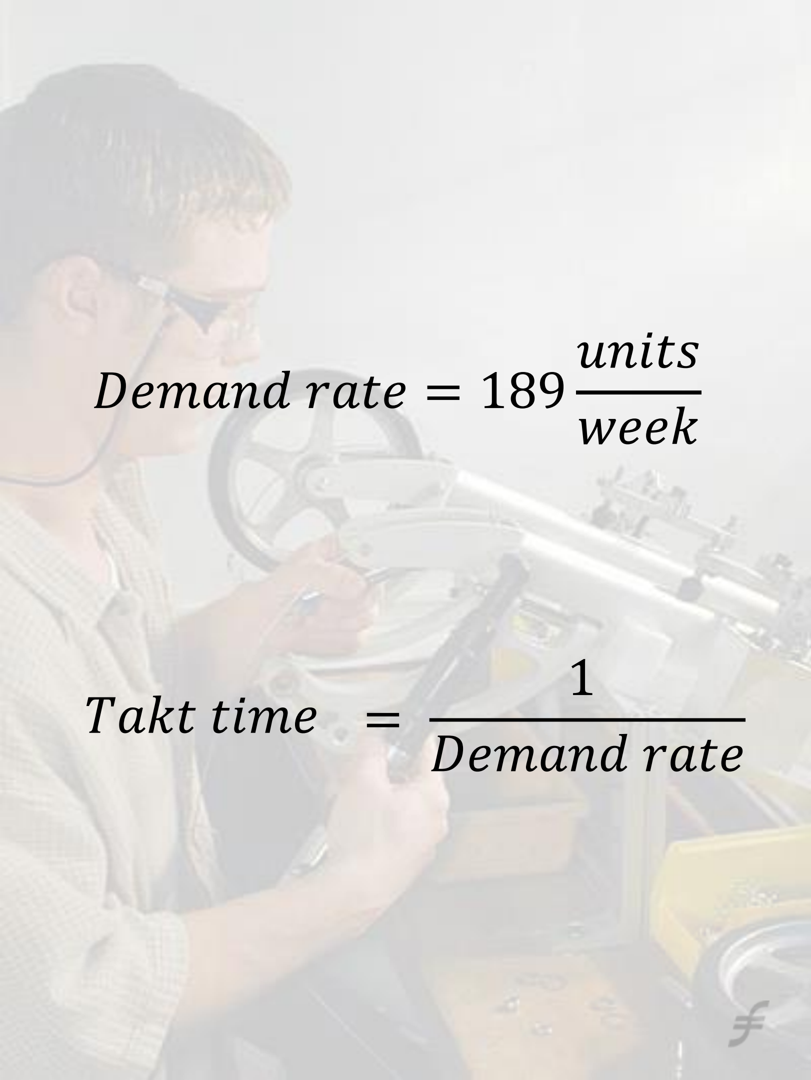
for activities with no fixed sequence

Heuristic approach

- Compute takt time.
- For each resource: keep on adding activities as long as processing time ≤ takt time.

- Extra flexibility allows better results.
- Optimization difficult (beyond this module).

# Takt Time



$$Demand\ rate = 189\,\frac{units}{week}$$

$$Takt\ time = \frac{1}{Demand\ rate}$$

# Re-assignment of Activities

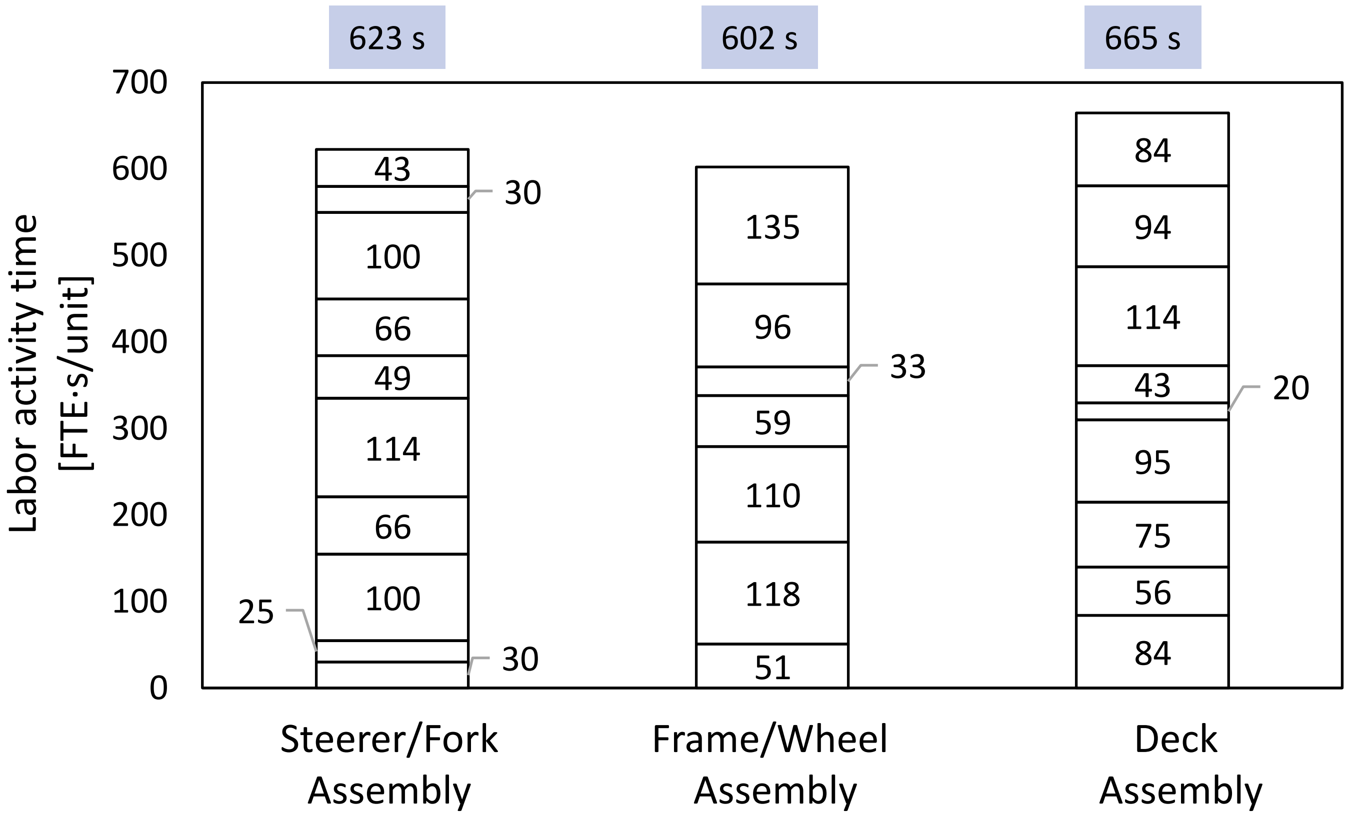
| Tasks | Time per activity* | Worker |
|---|---|---|
| #1 Prepare cable | 30 | |
| #2 Move cable | 25 | |
| #3 Assemble washer | 100 | |
| #4 Apply fork, threading cable end | 66 | |
| #5 Assemble socket head screws | 114 | |
| #6 Steer pin nut | 49 | |
| #7 Brake shoe, spring, pivot bolt | 66 | |
| #8 Insert front wheel | 100 | |
| #9 Insert axle bolt | 30 | |
| #10 Tighten axle bolt | 43 | |
| #11 Tighten brake pivot bolt | 51 | |
| #12 Assemble handle cap | 118 | |
| #13 Assemble brake lever | 110 | |

*in seconds

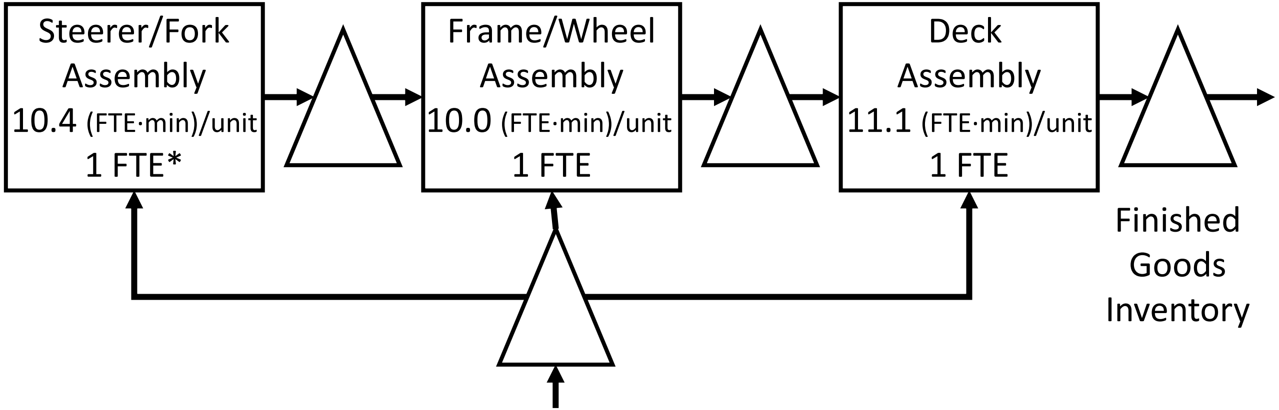
| Tasks | Time per activity* | Worker |
|---|---|---|
| #14 Trim and cap cable | 59 | |
| #15 Place first rib | 33 | |
| #16 Insert axles and cleats | 96 | |
| #17 Insert rear wheel | 135 | |
| #18 Place second rib and deck | 84 | |
| #19 Apply grip tape | 56 | |
| #20 Insert deck fasteners | 75 | |
| #21 Inspect and wipe off | 95 | |
| #22 Apply decal and sticker | 20 | |
| #23 Insert in bag | 43 | |
| #24 Assemble carton | 114 | |
| #25 Insert Xootr and manual | 94 | |
| #26 Seal carton | 84 | |

#14: Task number 14

# After Line Balancing



# Performance of the Balanced System




Worker work time: 35 hours/week

Workers get paid if they are idle

Demand rate: 189 units/week

# Performance of the Balanced System

$$\begin{array}{c}\mathit{Cost\ of}\\ \mathit{direct\ labor}\end{array} = \frac{1{,}260\,\frac{€}{week}}{189\,\frac{units}{week}} = 6.67\,\frac{€}{Unit}$$

$$\begin{array}{c}\mathit{Total}\\ \mathit{idle\ time}\end{array} = 11.1\,\frac{min}{unit}\cdot 3FTE - 31.5\,\frac{FTE\cdot min}{unit} = 1.8\,\frac{FTE\cdot min}{unit}$$

$$\begin{array}{c}\mathit{Average}\\ \mathit{labor}\\ \mathit{utilization}\end{array} = \frac{31.5\,\frac{FTE\cdot min}{unit}}{11.1\,\frac{min}{unit}\cdot 3FTE} = 0.9450$$

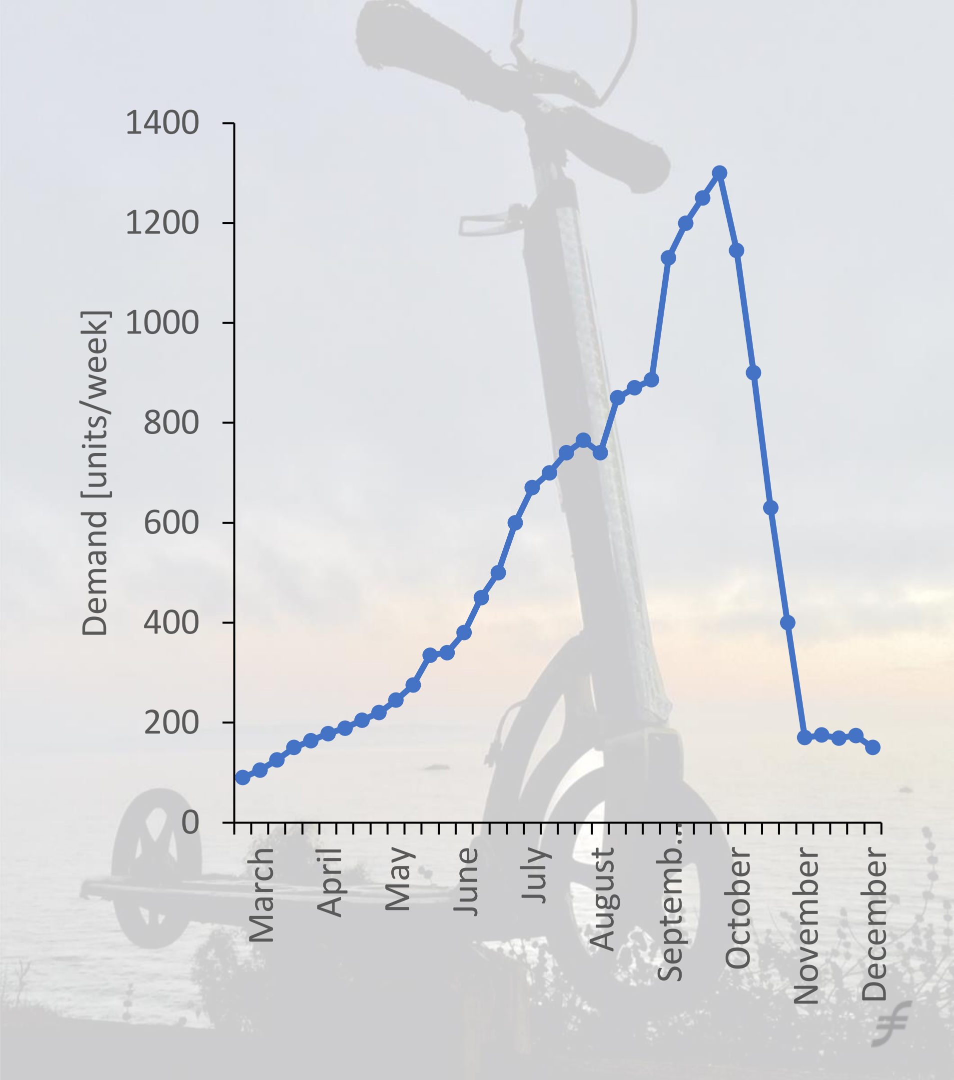
Demand rate:
189 units/week

Flow rate:
189 units/week

Cycle time:
11.1 min/unit

# Xootr Challenges

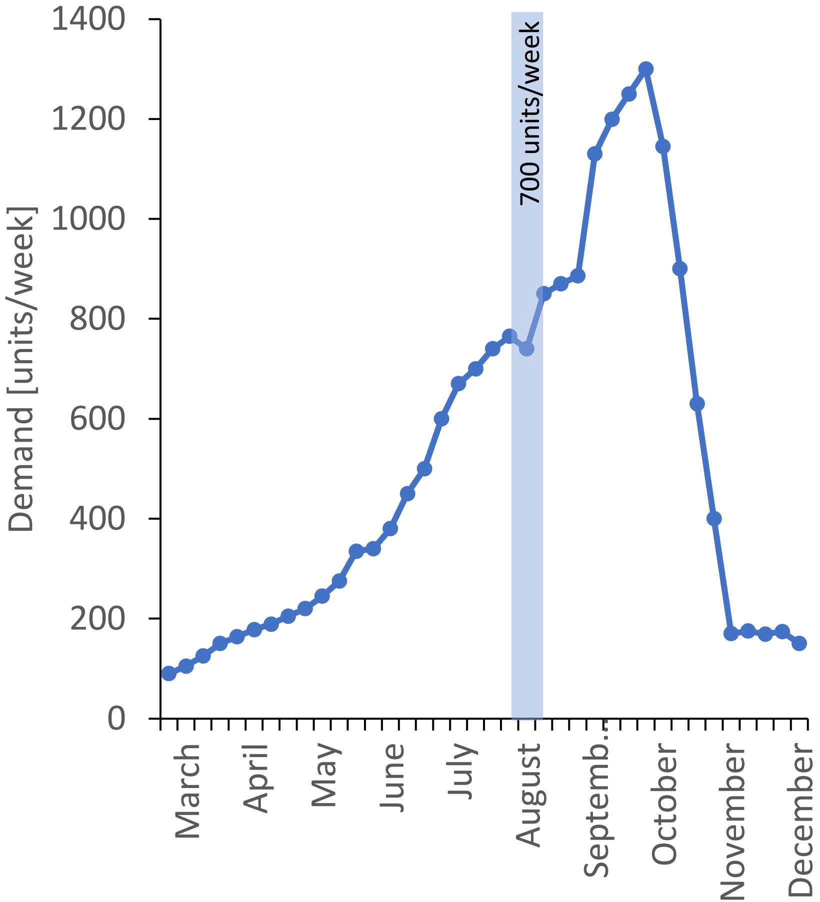
- How to measure process efficiency?
- How to improve process efficiency?
- **How to scale up production?**



# How to scale up production to 700 units/week?

- How much time do we have to produce one unit?

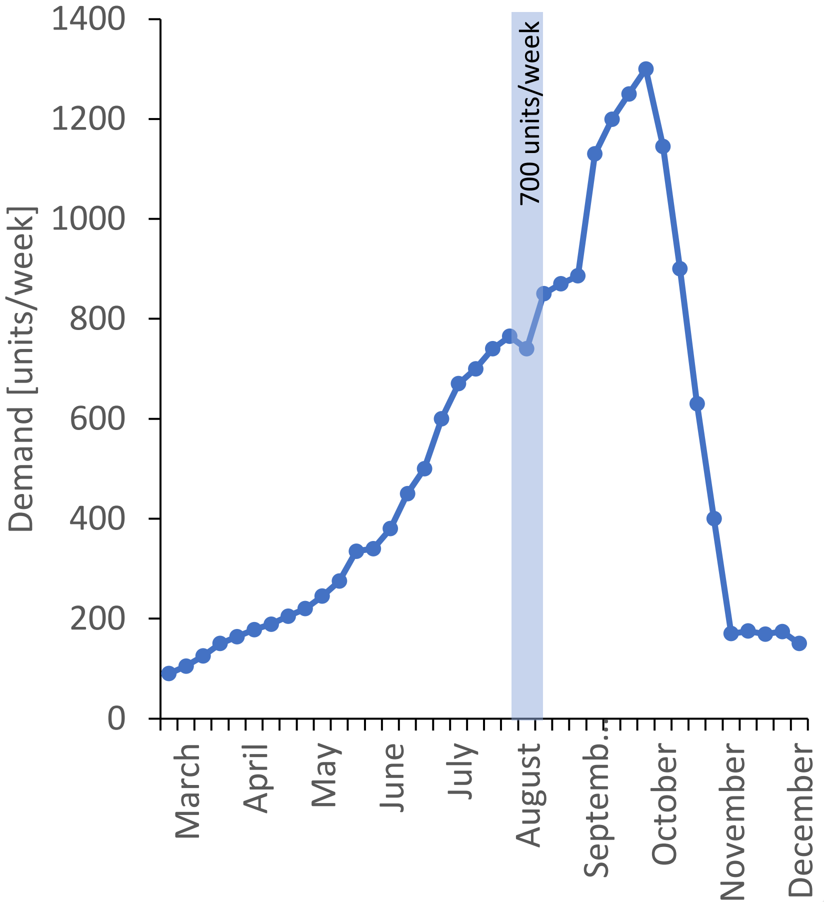
$$Takt\ time = \frac{1}{Demand\ rate}$$



# How to scale up production to 700 units/week?

- How many FTE do we need?

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



# Three Alternate Process Designs

- Specialization:
  one assembly line with many stations.
- Replication:
  a couple of parallel three-station lines.
- Generalization:
  many parallel work cells.

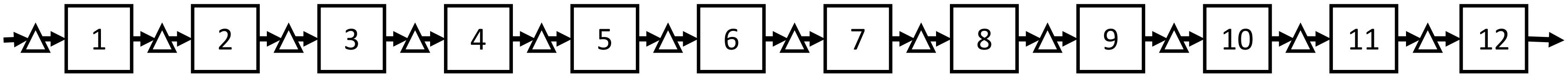
# Specialization – One Line With Many Stations

The line-balancing activity assignment rule is reused: For each resource, activities are added as long as processing time ≤ takt time

| Tasks | Time per activity [FTE·s/unit] | Worker 1 | Worker 2 | Worker 3 | … |
|---|---|---|---|---|---|
| #1 Prepare cable | 30 | 1 | 0 | 0 | |
| #2 Move cable | 25 | 1 | 0 | 0 | |
| #3 Assemble washer | 100 | 1 | 0 | 0 | |
| #4 Apply fork, threading cable end | 66 | 0 | 1 | 0 | |
| #5 Assemble socket head screws | 114 | 0 | 1 | 0 | |
| #6 Steer pin nut | 49 | 0 | 0 | 1 | |
| ... | | | | | |

How does the process look like?

# Specialization – One Line With Many Stations




Why do we need 12 stations (=12 FTE) instead of 10.5?

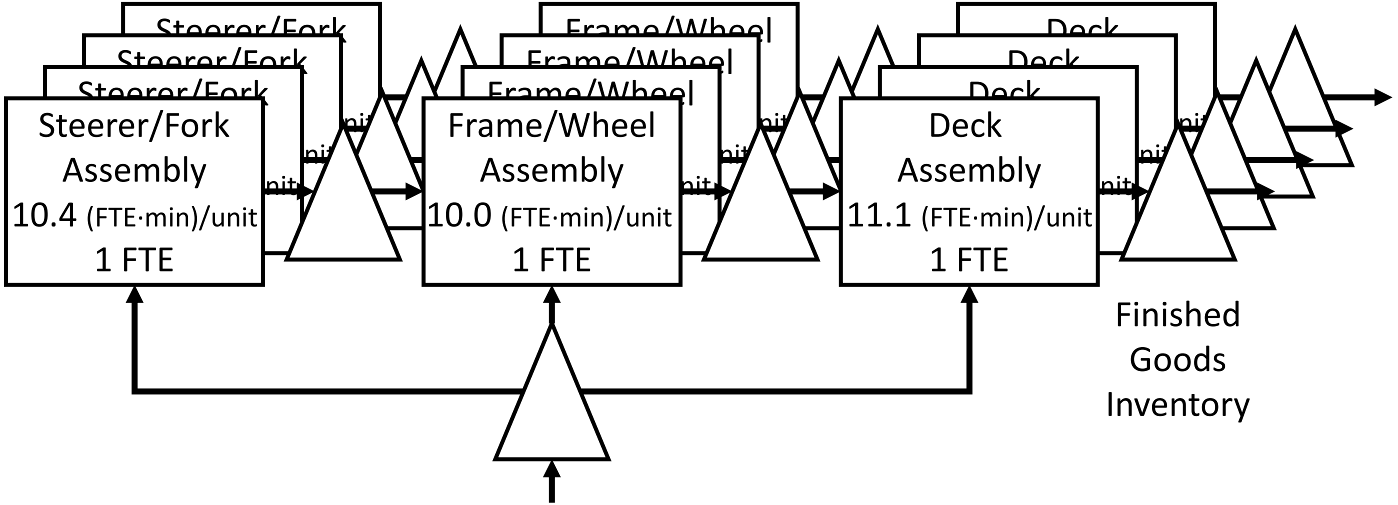
Advantages of specialization

Disadvantages of specialization

# Replication – Several Parallel Three-station Lines

Process capacity of one balanced line: 189.5 units/week

$$Number\ of\ lines = \frac{700\,\frac{units}{week}}{189.5\,\frac{units}{week}} = 3.7$$

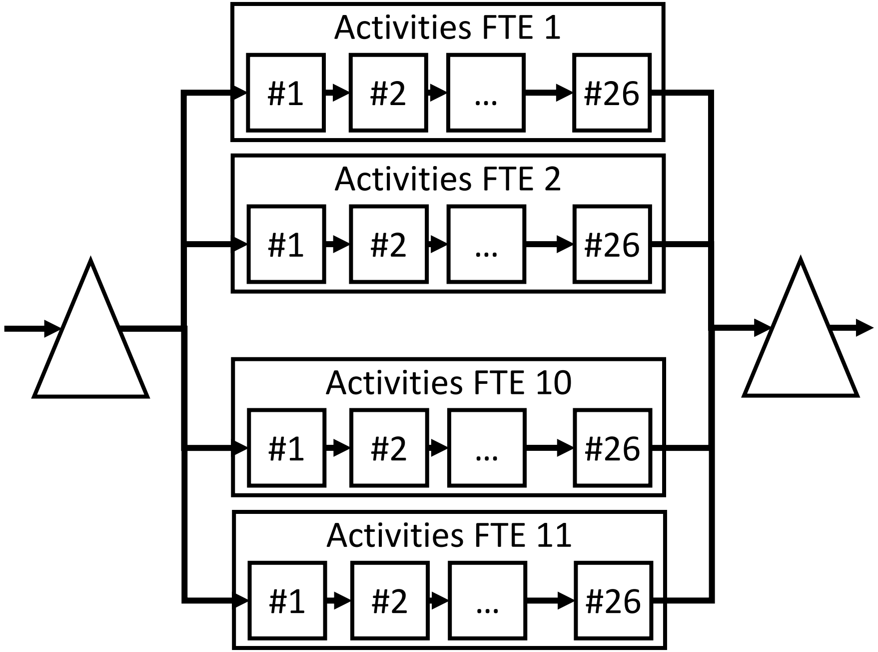


# Generalization - Many Parallel Work Cells

Assigning all activities to one work cell with one worker and use the target manpower formula and calculation:

$$\begin{array}{c} Target \\ manpower \end{array} = \frac{Labor\ content}{Takt\ time}$$

$$= 10.5\ FTE$$

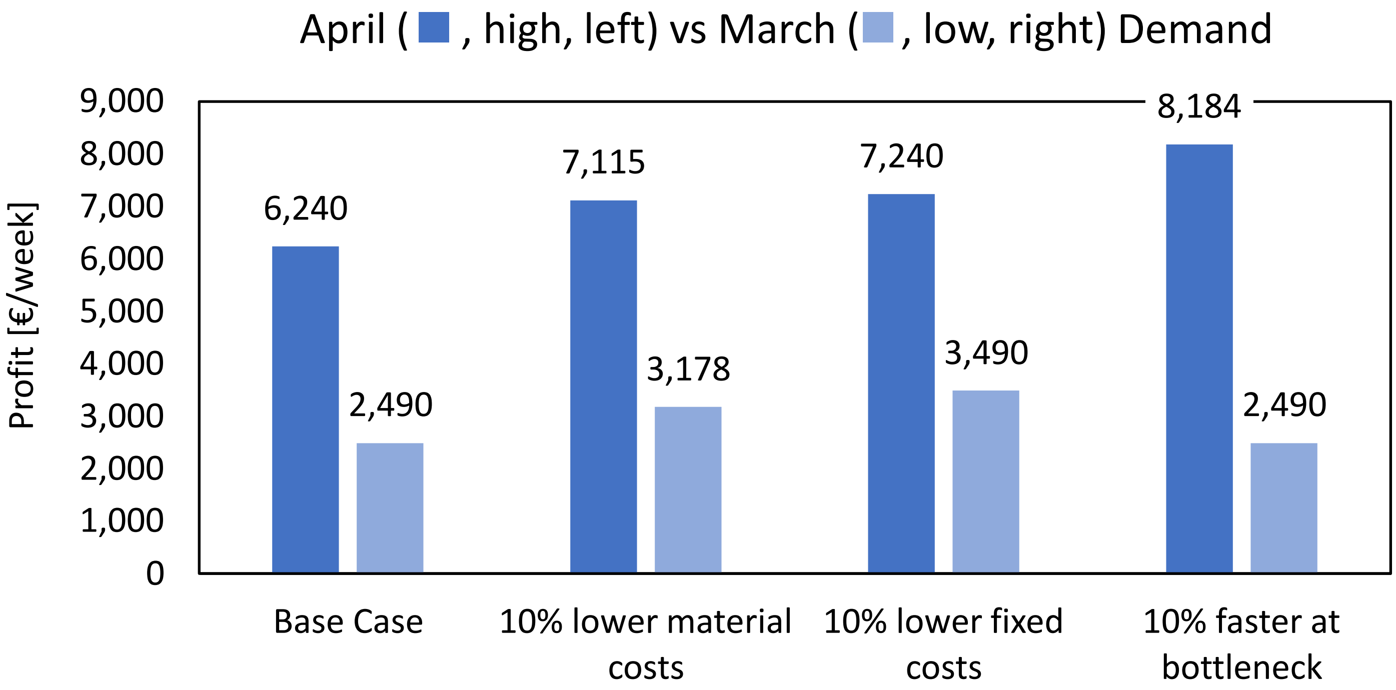


# Financial Impact of Process Improvement

- The goal of operations in for-profit organizations is to help generate profits.
- Operations in non-for-profit organizations should help to avoid losses.

$$Profit = Flow\ rate \cdot (Price - Variable\ costs) - Fixed\ costs$$

# Profit Implications of Different Improvement Scenarios



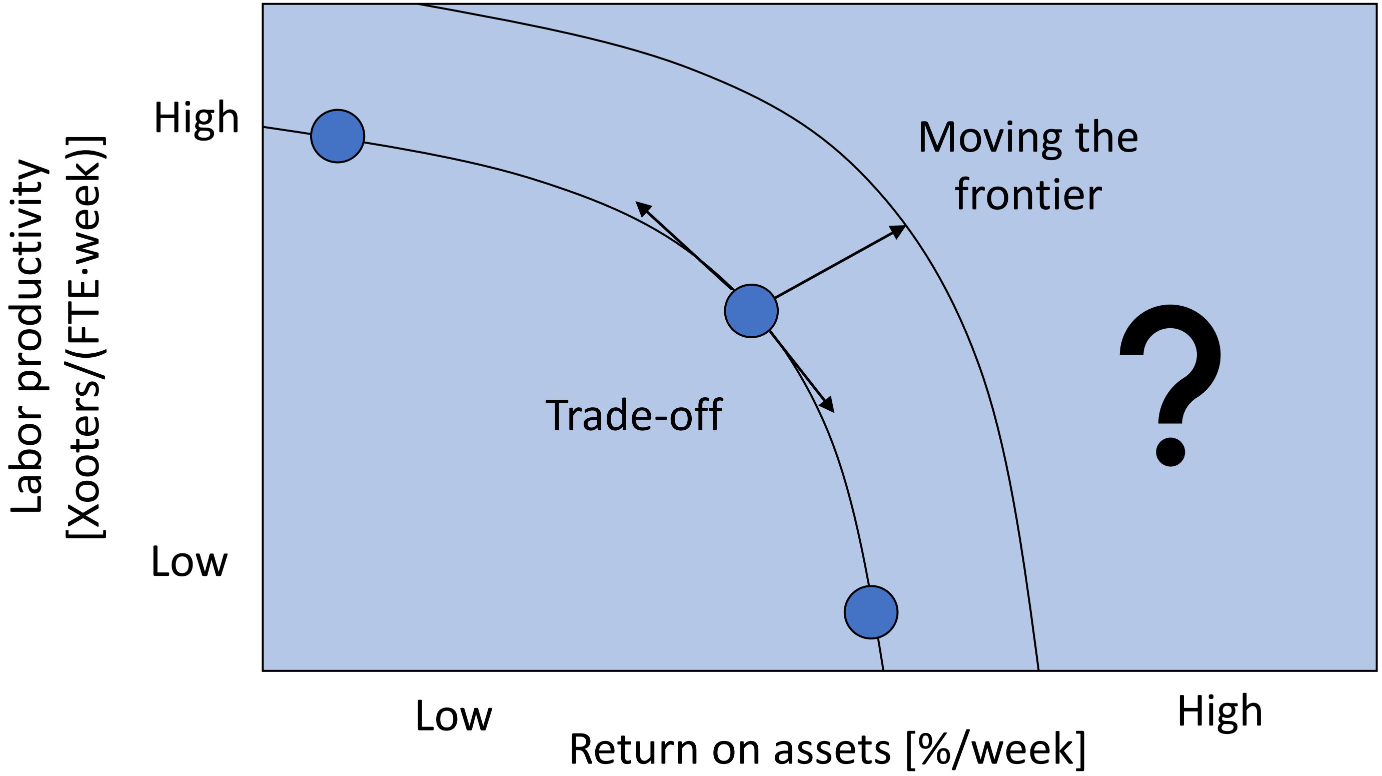

$$Selling\ price = 165\,\frac{€}{unit}$$

$$Material\ costs = 55\,\frac{€}{unit}$$

$$Labor\ costs = 12\,\frac{€}{FTE \cdot h}$$

$$Fixed\ costs = 10.000\,\frac{€}{week}$$

# Assessing the Impact of Line Balancing



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# 2023 Operations Management

# PROCESS ANALYSIS WITH MULTIPLE FLOWS

# MULTIPLE FLOW UNITS,
# SAME PROCESSING TIMES

# Capital One

- Capital One mission: help our customers succeed by bringing ingenuity, simplicity, and humanity to banking.
- Founded on the belief that the banking industry would be revolutionized by information and technology, beginning with credit cards.
- Today fifth-largest consumer bank and eighth-largest bank overall in the US.




https://www.capitalone.com/about/corporate-information/

# Capital One Small Loans Department Challenges

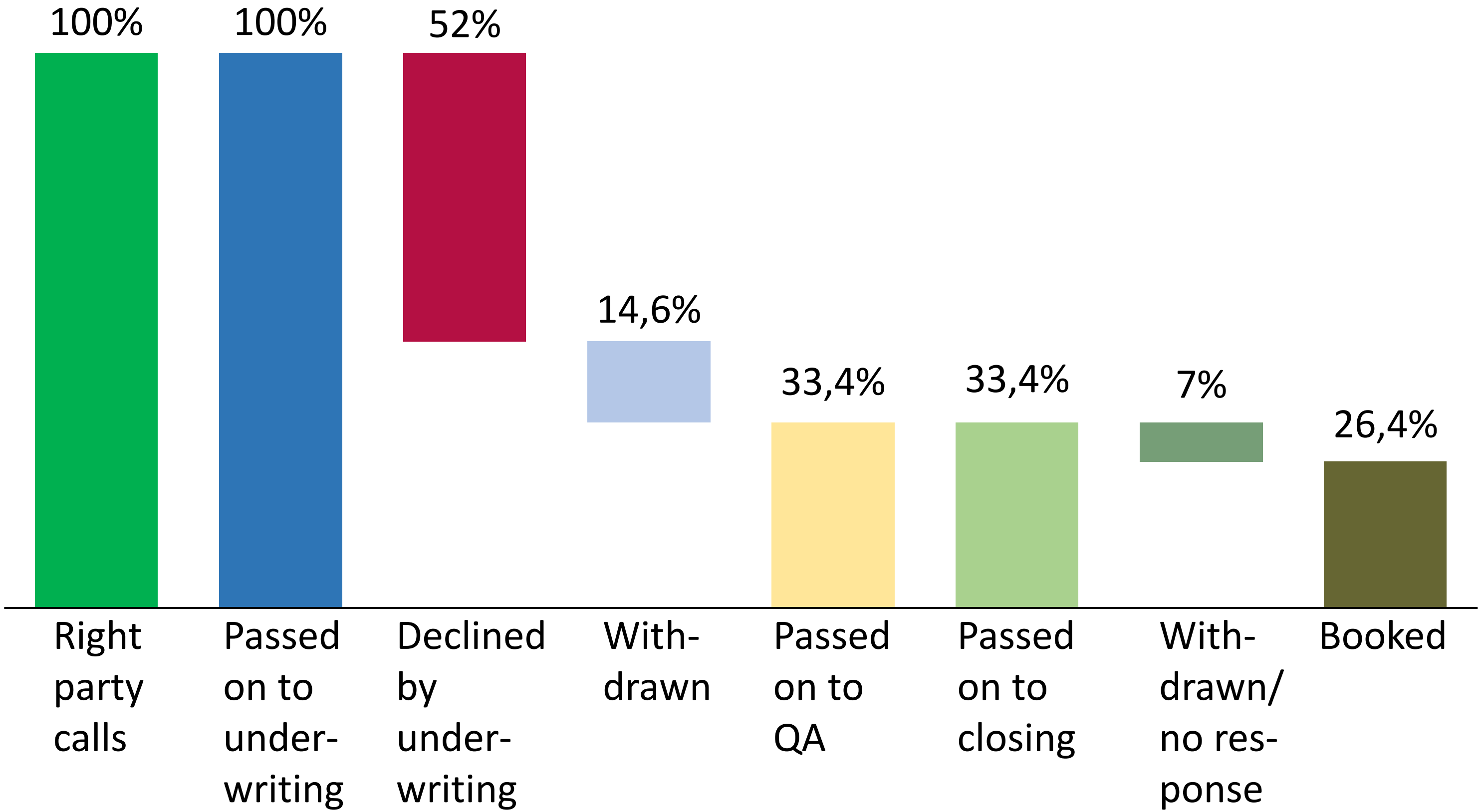
- How to determine demand for resources in a process with multiple flow units?
- How to find the bottleneck in a general process flow (with multiple flow units)?

**Capital One Loan Approval Process**

The marketing department solicits potential customers through direct mail and/or e-mail campaigns. Customers can answer by returning information concerning their name, the type of loan they are interested in, etc. This starts the loan approval process. It consists of the following five steps:

- An employee interviews the customer about his or her financial needs and collects all required information;
- Underwriting is the step where the decision of awarding the loan is made;
- Quality assurance is reviewing all documents prepared by the underwriter;
- Closing is in charge to print all relevant documents, prepare them for submission to the customer, and to call the customer to inform him or her that the loan is approved;
- The manager signs the final paperwork and releases the payment.

# Not Every Customer Receives a Loan

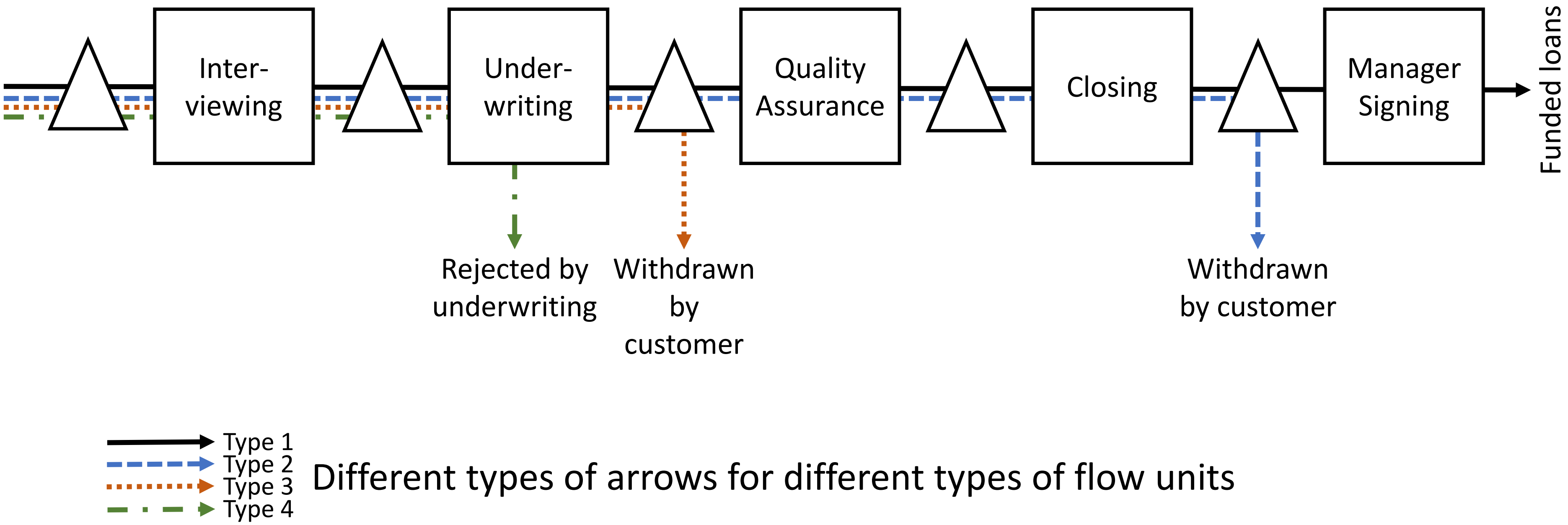


# Demand Rates of Different Types of Flow Units

- On average, the Capital One loans department receives 110 loan applications per day by customers in total.
- This results in the following flow unit demand rates:

| | Demand rate | |
|---|---|---|
| Type 1 (funded loans) | 29.04 | apps/day |
| Type 2 (withdrawn after closing) | 7.70 | apps/day |
| Type 3 (withdrawn after underwriting) | 16.06 | apps/day |
| Type 4 (rejected by underwriting) | 57.20 | apps/day |
| Total | 110.00 | apps/day |

# Process Flow Diagram Showing Multiple Flow Units




Different types of arrows for different types of flow units

# Demand Table

- A table depicting the resources (rows) and demand flows (columns) through a process.
- Integrates information from the process flow diagram with flow unit demand rates.

| Resource | Flow unit<br>Type 1 [apps/day] | Type 2 [apps/day] | Type 3 [apps/day] | Type 4 [apps/day] | Total Demand [apps/day] |
|---|---|---|---|---|---|
| Interviewer | 29.04 | 7.70 | 16.06 | 57.20 | 110.00 |
| Underwriter | 29.04 | 7.70 | 16.06 | 57.20 | 110.00 |
| Quality assurance specialist | 29.04 | 7.70 | 0 | 0 | 36.74 |
| Closing employee | 29.04 | 7.70 | 0 | 0 | 36.74 |
| Manager | 29.04 | 0 | 0 | 0 | 29.04 |

# Capital One Small Loans Department Challenges

- How to determine demand for resources in a process with multiple flow units?
- How to find the bottleneck in a general process flow (with multiple flow units)?

**Capital One Loan Approval Process**

The marketing department solicits potential customers through direct mail and/or e-mail campaigns. Customers can answer by returning information concerning their name, the type of loan they are interested in, etc. This starts the loan approval process. It consists of the following five steps:

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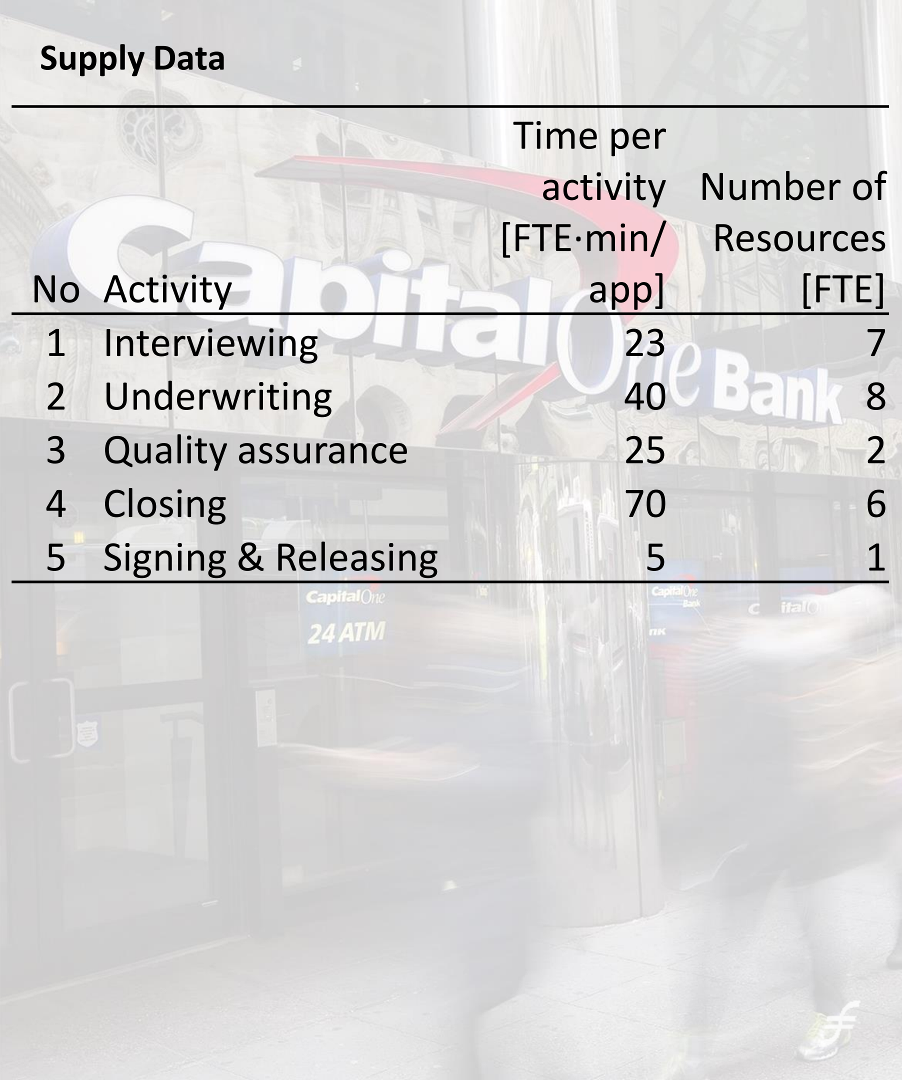
- Closing is in charge to print all relevant documents, prepare them for submission to the customer, and to call the customer to inform him or her that the loan is approved;
- The manager signs the final paperwork and releases the payment.

# Calculation of Capacity at Capital One

$$Capacity = \frac{\#FTE}{Processing\ time}$$

$$Capacity(Interviewers) =$$




**Supply Data**

| No | Activity | Time per activity [FTE·min/ app] | Number of Resources [FTE] |
|---|---|---|---|
| 1 | Interviewing | 23 | 7 |
| 2 | Underwriting | 40 | 8 |
| 3 | Quality assurance | 25 | 2 |
| 4 | Closing | 70 | 6 |
| 5 | Signing & Releasing | 5 | 1 |

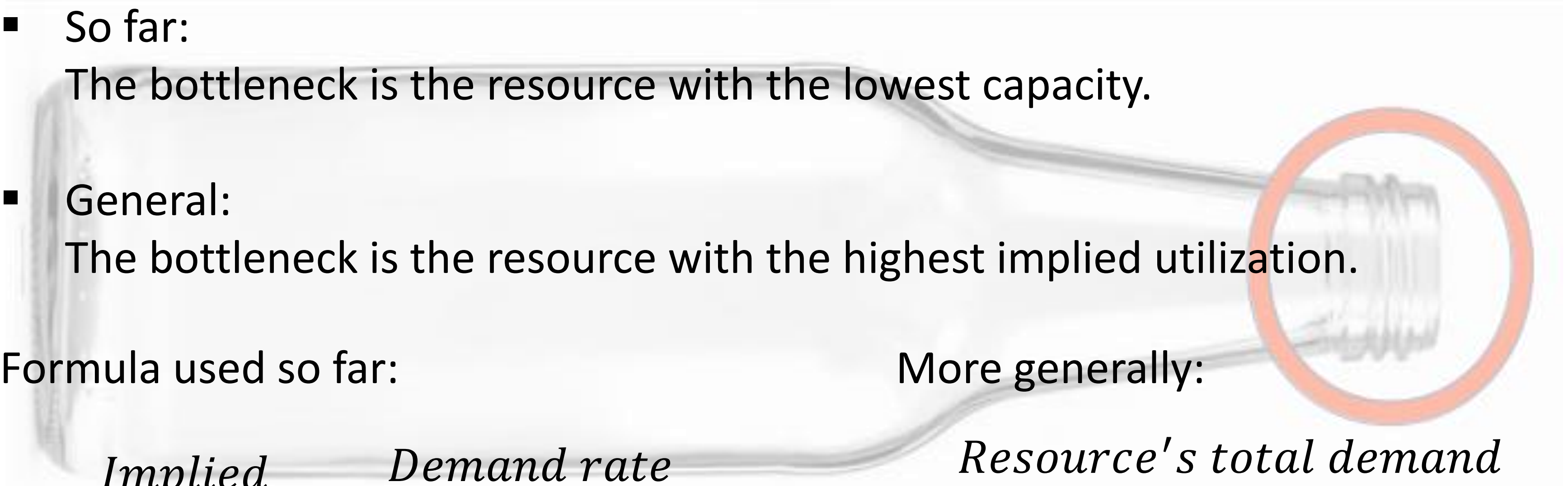
Recall: #FTE equivalent to m

# Capacity Levels at Capital One

| Resource | Capacity [apps/min] | Capacity [apps/day] |
|---|---:|---:|
| Interviewers | 0.3043 | 121.74 |
| Underwriters | 0.2000 | 80.00 |
| Quality assurance specialists | 0.0800 | 32.00 |
| Closing employees | 0.0857 | 34.29 |
| Manager | 0.2000 | 80.00 |

- Net work time at Capital One: 400 min/day
- Where is the bottleneck?

# A General Definition of a Bottleneck



- So far:
  The bottleneck is the resource with the lowest capacity.

- General:
  The bottleneck is the resource with the highest implied utilization.

Formula used so far:

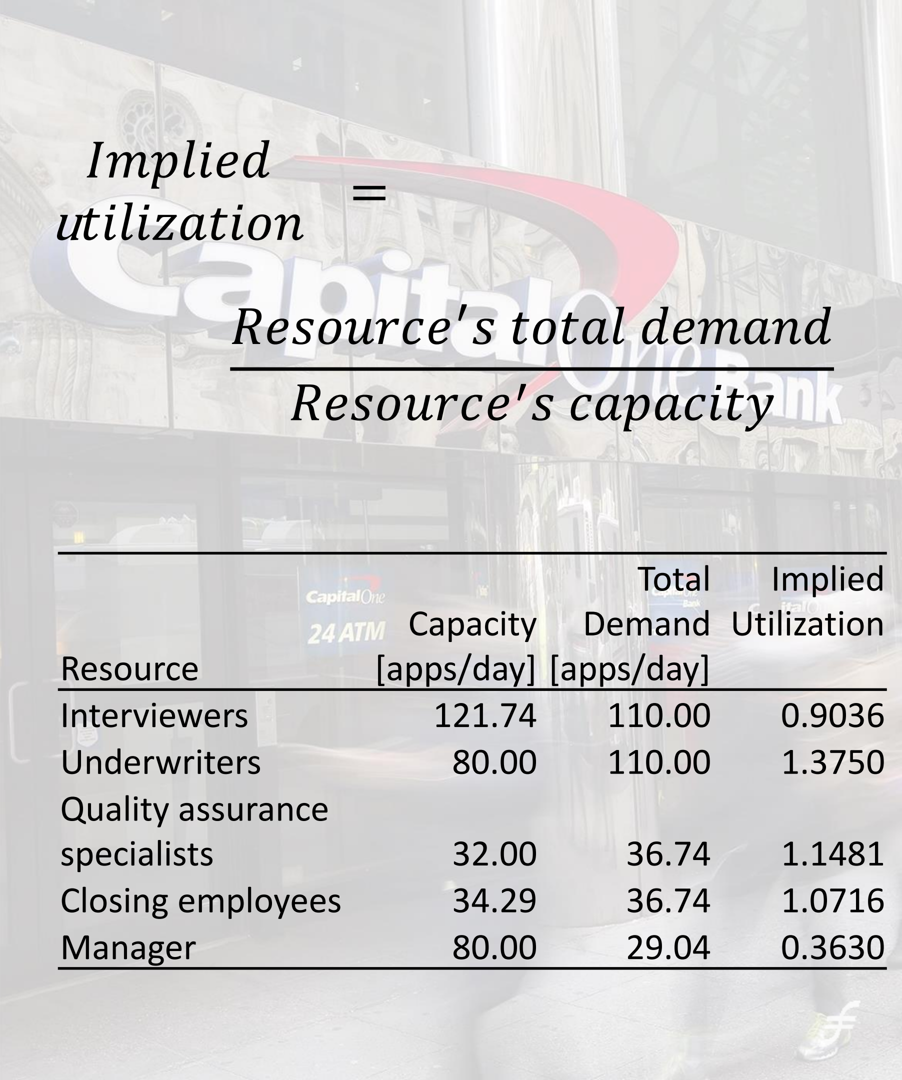
$$\begin{array}{c}\textit{Implied}\\ \textit{utilization}\end{array} = \frac{\textit{Demand rate}}{\textit{Capacity}}$$

More generally:

$$= \frac{\textit{Resource's total demand}}{\textit{Resource's capacity}}$$

# Calculation of Implied Utilization

$$\begin{array}{c} Implied\ utilization \\ (Interviewers) \end{array} = \frac{110\left[\frac{apps}{day}\right]}{121.74\ \left[\frac{apps}{day}\right]} = 0.9036$$



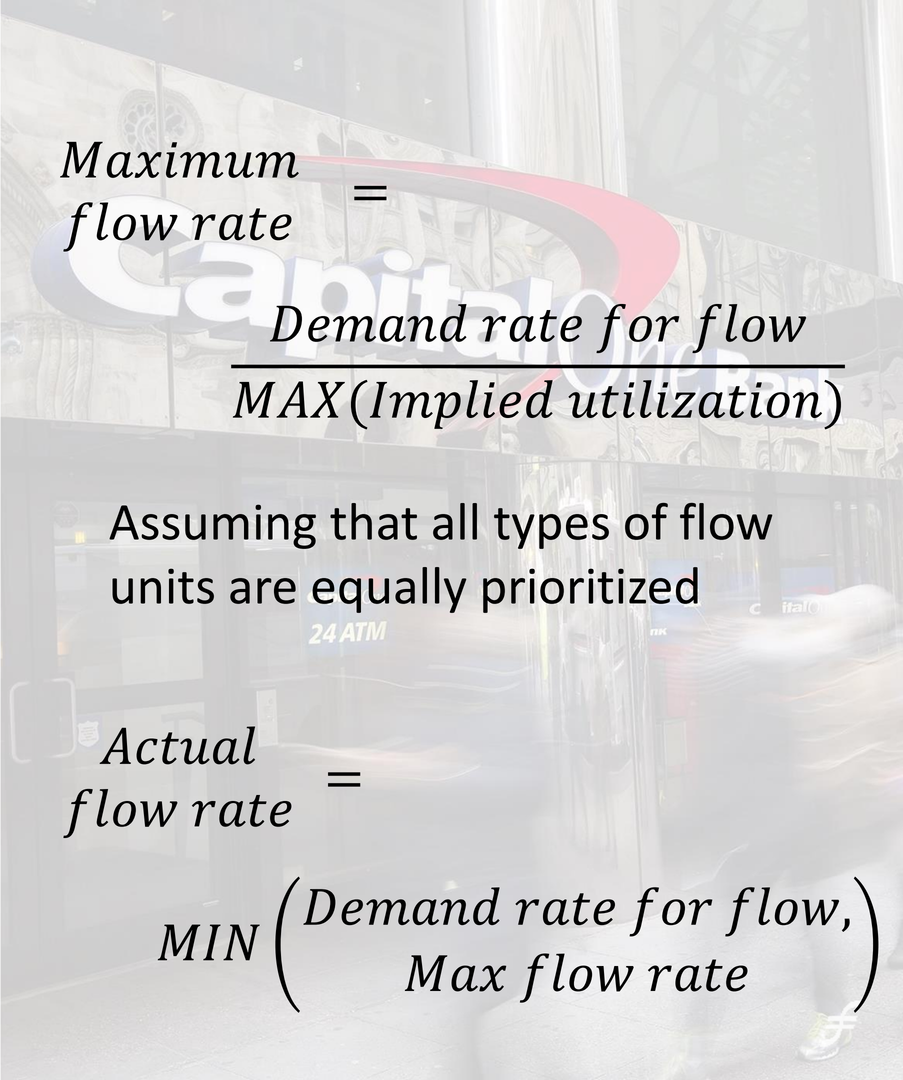

$$\begin{array}{c} Implied \\ utilization \end{array} = \frac{Resource's\ total\ demand}{Resource's\ capacity}$$

| Resource | Capacity [apps/day] | Total Demand [apps/day] | Implied Utilization |
|---|---|---|---|
| Interviewers | 121.74 | 110.00 | 0.9036 |
| Underwriters | 80.00 | 110.00 | 1.3750 |
| Quality assurance specialists | 32.00 | 36.74 | 1.1481 |
| Closing employees | 34.29 | 36.74 | 1.0716 |
| Manager | 80.00 | 29.04 | 0.3630 |

# Maximum and Actual Flow Rates

$$Max\ flow\ rate(Type\ 1) =$$

$$Max\ flow\ rate(all\ types) =$$




$$\begin{matrix} Maximum \\ flow\ rate \end{matrix} = \frac{Demand\ rate\ for\ flow}{MAX(Implied\ utilization)}$$

Assuming that all types of flow units are equally prioritized

$$\begin{matrix} Actual \\ flow\ rate \end{matrix} = MIN\begin{pmatrix} Demand\ rate\ for\ flow, \\ Max\ flow\ rate \end{pmatrix}$$

# How to find the bottleneck and the flow rates in a process with multiple flows?

- Step 1
  Evaluate the demand table, with rows representing resources and columns representing different flows.

- Step 2
  Evaluate the capacity for each resource. Be sure that the capacity is given in the same time unit as the demand rate.

- Step 3
  Evaluate the implied utilization for each resource in the process:

$$\begin{matrix} Implied \\ utilization \end{matrix} = \frac{Resource's\ total\ demand}{Resource's\ capacity}$$

The resource with the highest implied utilization is the bottleneck.

- Step 4
  If capacity is divided proportionally to demand for different type of flow units

$$\begin{matrix} Maximum \\ flow\ rate \end{matrix} = \frac{Demand\ rate\ for\ flow}{MAX(Implied\ utilization)}$$

Demand-constrained process: actual flow rates equal the demand rates.
Supply-constrained process: actual flow rates equal maximum flow rates.

# TYPE OF FLOW UNIT DEPENDENT PROCESSING TIMES

# Urgent Care Clinic

- Provides health care services to patients who feel sick but cannot get a timely appointment.
- Patients with severe conditions go to the emergency unit of the local hospital.
- Deals with mild cases, but can provide imaging diagnostic (x-ray) and some lab analysis.

# Urgent Care Clinic Challenge

- How to find the bottleneck in a general process flow (with flow-dependent processing times)?

**Five type of patients**

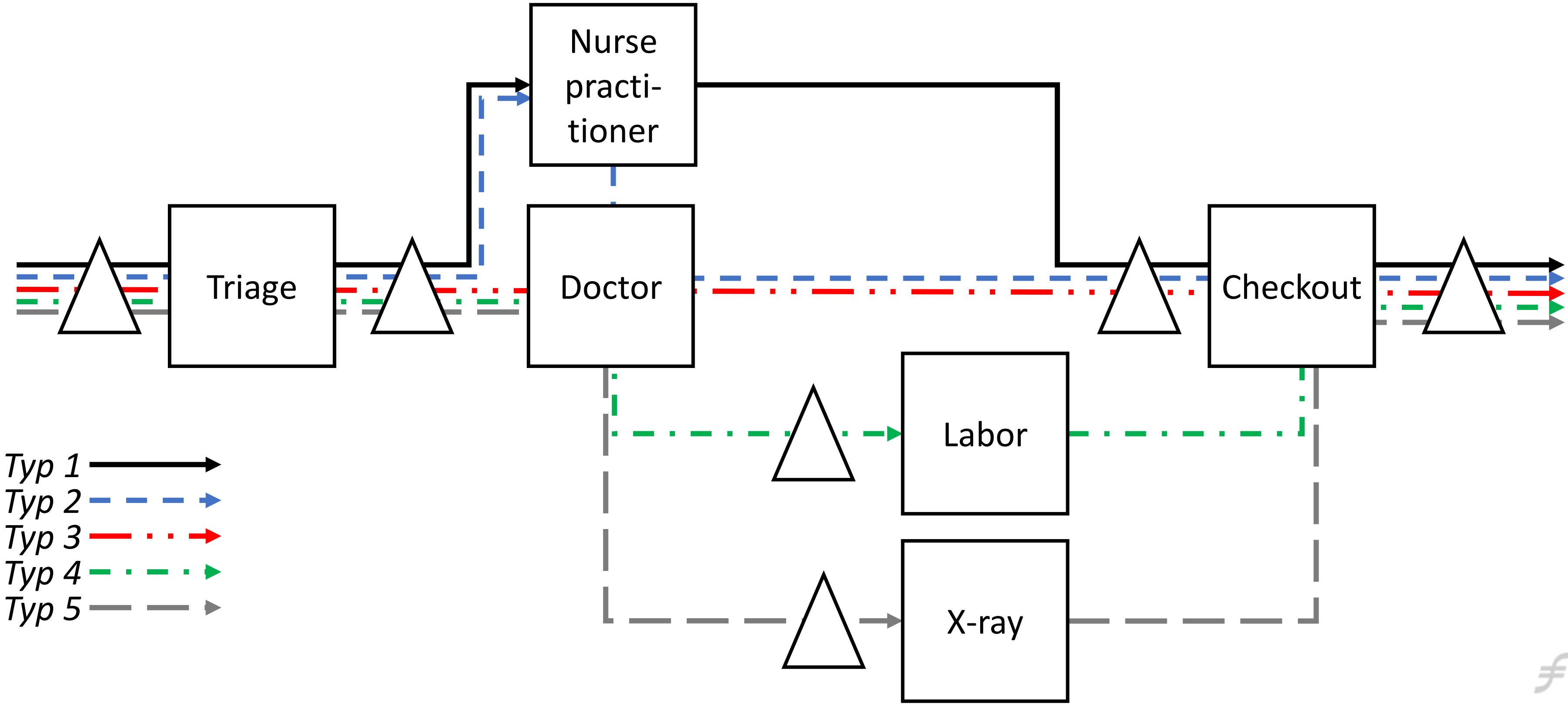
All patients go through an initial greeting and diagnosing stage (triage) and a final checkout step.

- Type 1 patients have only minor ailments and are seen by the nurse practitioner only;
- Type 2 patients are seen by the nurse practitioner, but the nurse practitioner also wants the doctor to look at the patient;
- Type 3 patients are seen by the doctor only;
- Type 4 patients are seen by the doctor, who the requests labs;
- Type 5 patients are seen by the doctor, who then requests X-rays.

| | Demand for care | |
|---|---|---|
| Patient types | [cases/day] | [cases/h] |
| Type 1: Nurse only | 20 | 2 |
| Type 2: Nurse and doctor | 5 | 0.5 |
| Type 3: Doctor only | 15 | 1.5 |
| Type 4: Doctor with labs | 15 | 1.5 |
| Type 5: Doctor with X-rays | 8 | 0.8 |

A day consists of 10 hours.

# Process Flow Diagram



# Flow-dependent Processing Times

| | Processing times [FTE · min/case] | | | | | |
|---|---|---|---|---|---|---|
| Patient types | Triage nurse | Nurse practitioner | Doctor | Lab | X-ray | Check-out clerk |
| Type 1: Nurse only | 6 | 20 | 0 | 0 | 0 | 4 |
| Type 2: Nurse and doctor | 6 | 30 | 5 | 0 | 0 | 4 |
| Type 3: Doctor only | 6 | 0 | 15 | 0 | 0 | 4 |
| Type 4: Doctor with labs | 6 | 0 | 20 | 5 | 0 | 4 |
| Type 5: Doctor with X-rays | 6 | 0 | 20 | 0 | 20 | 4 |

# Abstract Flow Unit “One Minute of Work”

- With patient type dependent processing times, using “one patient” or “one patient” as flow unit is no longer adequate.
- Consistent measurement of capacity “Patient/Hour” would not be possible.
- Changing the flow unit to the abstract concept of “one minute of work” is necessary.

# Demand Rate

- Consider again the nurse practitioner.
- Type 1 patients require 20 minutes of work, and type 2 patients 30 minutes.
- Type 3 to 5 patients require no work at all.

$$Demand\ for\ work\ at\ resource\ i = \sum_{Type=1}^{n} p_{Type,i} \cdot d_{Type}$$

$p$: processing time, $d$: demand

For example, demand for the nurse practitioner resource in minutes of work per hour:

$$= 2.0 \left[\frac{cases}{h}\right] \cdot 20 \left[\frac{FTE \cdot min}{case}\right] + 0.5 \left[\frac{cases}{h}\right] \cdot 30 \left[\frac{FTE \cdot min}{case}\right] = 55 \left[\frac{FTE \cdot min}{h}\right]$$

# Demand Rate in Minutes of Work

| | Demand for work created by patient | | | | | |
|---|---|---|---|---|---|---|
| Resource | Type 1 | Type 2 | Type 3 | Type 4 | Type 5 | Total |
| Triage nurse | 12 | 3 | 9 | 9 | 4.8 | 37.8 |
| Nurse practitioner | 40 | 15 | 0 | 0 | 0 | 55 |
| Doctor | 0 | 2.5 | 22.5 | 30 | 16 | 71 |
| Lab | 0 | 0 | 0 | 7.5 | 0 | 7.5 |
| X-ray | 0 | 0 | 0 | 0 | 16 | 16 |
| Checkout clerk | 8 | 2 | 6 | 6 | 3.2 | 25.2 |

in [FTE·min/h]

# Capacity

| Resource | #FTE<br>[FTE] | Capacity<br>[FTE· min/h] |
|---|---|---|
| Triage nurse | 1 | 60 |
| Nurse practitioner | 2 | 120 |
| Doctor | 1 | 60 |
| Lab | 1 | 60 |
| X-ray | 1 | 60 |
| Checkout clerk | 1 | 60 |

$$\begin{matrix} Capacity\ at \\ resource\ i \end{matrix} = \#\mathrm{FTE}(i) \cdot 60 \left[\frac{min}{h}\right]$$

For example

$$\begin{matrix} Nurse \\ practitioner \\ capacity \end{matrix} = 2[FTE] \cdot 60 \left[\frac{min}{h}\right]$$

$$= 120 \left[\frac{FTE \cdot min}{h}\right]$$

# Calculation of Implied Utilization

$$\begin{matrix}\textit{Implied utilization} \\ (\textit{Nurse practitioner})\end{matrix} = \frac{55\left[\frac{FTE \cdot min}{h}\right]}{120\left[\frac{FTE \cdot min}{h}\right]} = 0.4583$$

$$\begin{matrix}\textit{Implied} \\ \textit{utilization}\end{matrix} = \frac{\textit{Demand rate in minutes of work}}{\textit{Capacity in minutes of work}}$$

| Resource | Capacity [FTE·min/h] | Demand [FTE·min/h] | Implied utilization [dmnl] |
|---|---:|---:|---:|
| Triage nurse | 60 | 37.8 | 0.6300 |
| Nurse practitioner | 120 | 55.0 | 0.4583 |
| Doctor | 60 | 71.0 | 1.1833 |
| Lab | 60 | 7.5 | 0.1250 |
| X-ray | 60 | 16.0 | 0.2667 |
| Checkout clerk | 60 | 25.2 | 0.4200 |

# How to find the bottleneck and the flow rates in a process with flow-dependent processing times?

- Step 1
  Compute the workload for each resource and type of demand.
- Step 2
  Sum the workloads for each resource across all demand types.
- Step 3
  Compute each resource's capacity (available working time).
- Step 4
  For each resource, compute:

$$\begin{matrix}Implied\\ utilization\end{matrix} = \frac{Demand\ rate\ in\ minutes\ of\ work}{Capacity\ in\ minutes\ of\ work}$$

The resource with the highest implied utilization is the bottleneck.

- Step 5
  If capacity is divided proportionally to demand for different type of flow units:

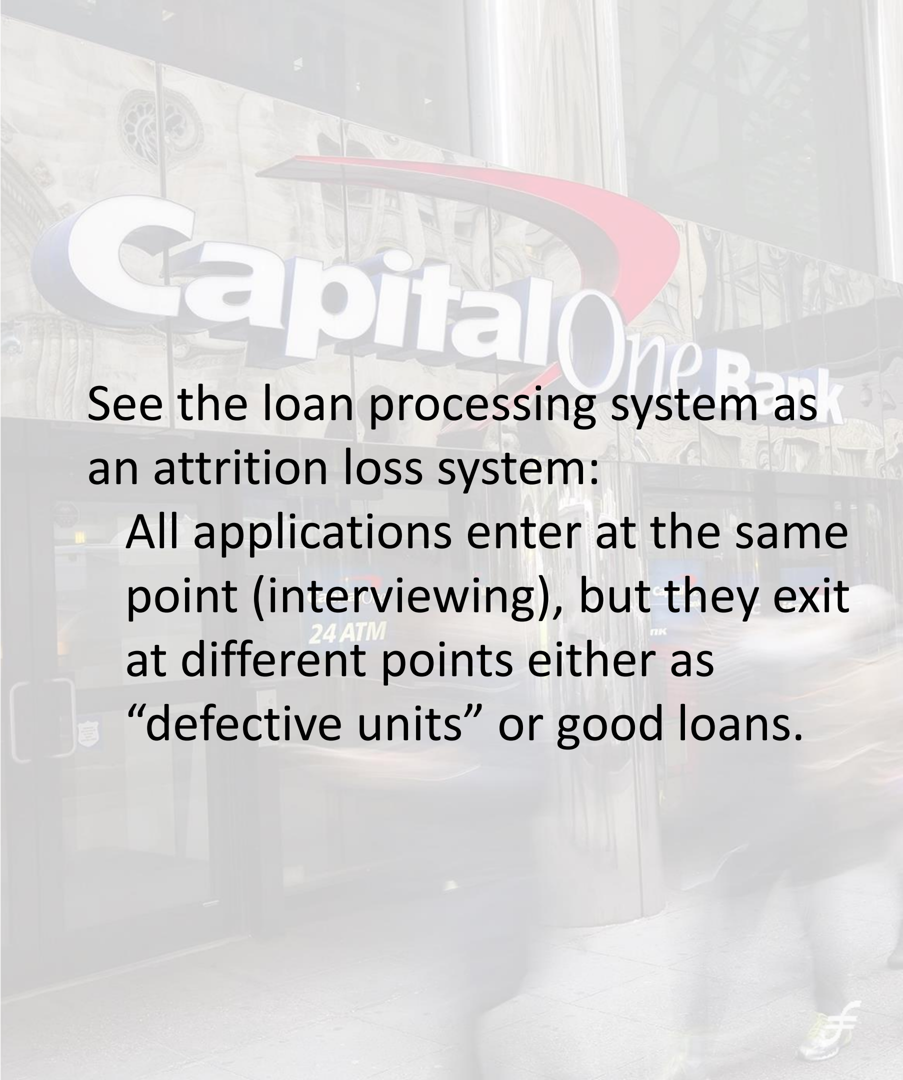
$$\begin{matrix}Maximum\\ flow\ rate\end{matrix} = \frac{Demand\ rate\ for\ flow}{MAX(Implied\ utilization)}$$

Demand-constrained process: actual flow rates = demand rates.
Supply-constrained process: actual flow rates = maximum flow rates.

# ATTRITION LOSS SYSTEMS

# Two Additional Capital One Challenges

- How many interviews to conduct to get a certain output Q of funded loans?
- What capacity of each resource is needed to produce a certain output Q of funded loans?




See the loan processing system as an attrition loss system:

All applications enter at the same point (interviewing), but they exit at different points either as “defective units” or good loans.

# Calculation of the Yield of a Resource

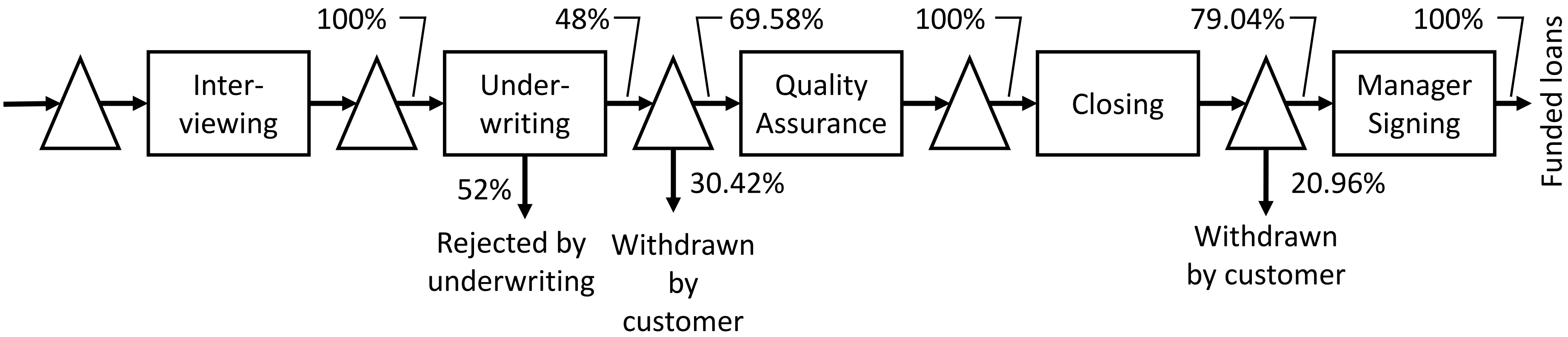
$$Yield\ of\ resource = \frac{Flow\ rate\ of\ good\ output\ at\ the\ resource}{Flow\ rate\ of\ input}$$

$$1 - \frac{Flow\ rate\ of\ defects\ at\ the\ resource}{Flow\ rate\ of\ input}$$

$$Process\ yield = \frac{Flow\ rate\ of\ good\ output\ of\ the\ process}{Flow\ rate\ of\ input\ to\ the\ process}$$

$$1 - \frac{Flow\ rate\ of\ defects\ in\ the\ process}{Flow\ rate\ of\ input\ to\ the\ process}$$

# Process Flow Diagram Showing Attrition Losses



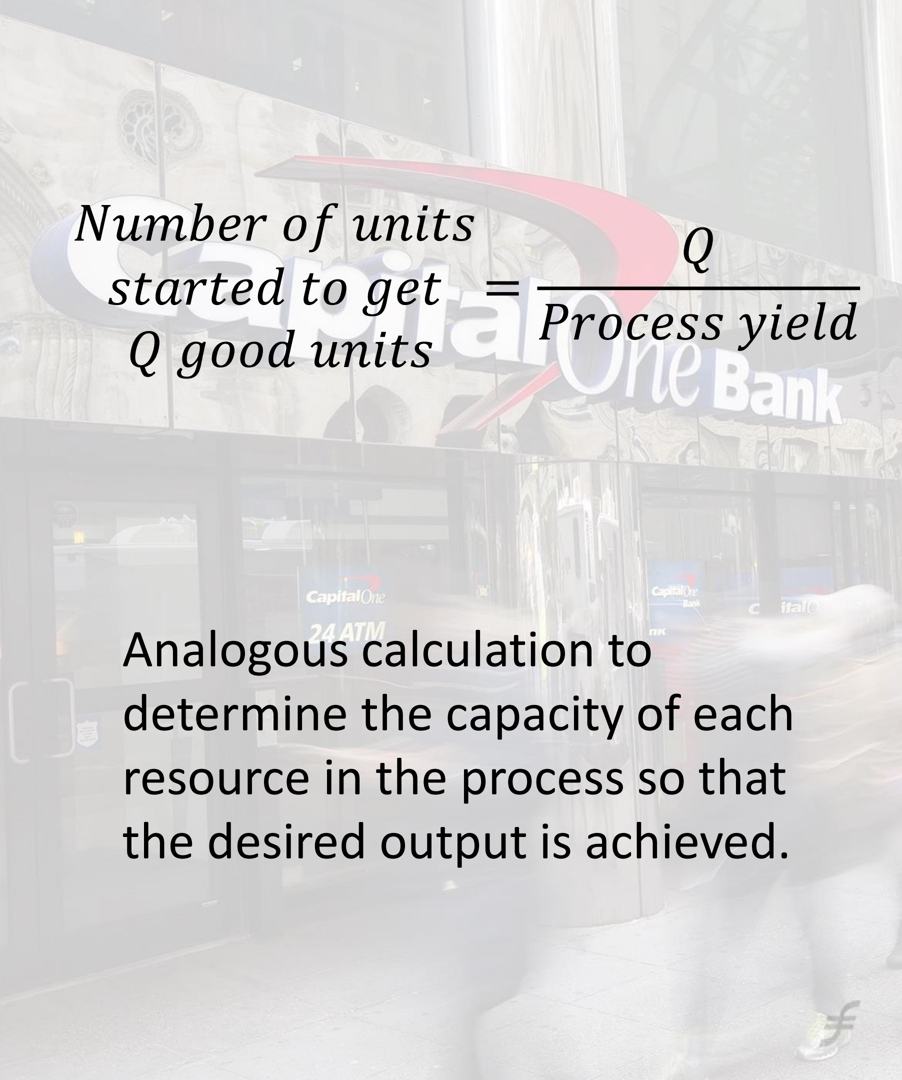

$$Process\ yield = 1 \cdot 0.48 \cdot 0.6958 \cdot 1 \cdot 0.7904 \cdot 1 = 0.264 \left[\frac{good\ apps}{app}\right]$$

$$Yield\ of\ underwriters = \frac{33.4\ [good\ apps]}{100[apps]} = 0.334 \left[\frac{good\ apps}{app}\right]$$

# Number of Interviews to Conduct

- Assume that Capital One sets the goal to have an output of 100 funded loans (good apps):

$$\begin{array}{l} Number\ of \\ interviews \\ to\ conduct \end{array} =$$



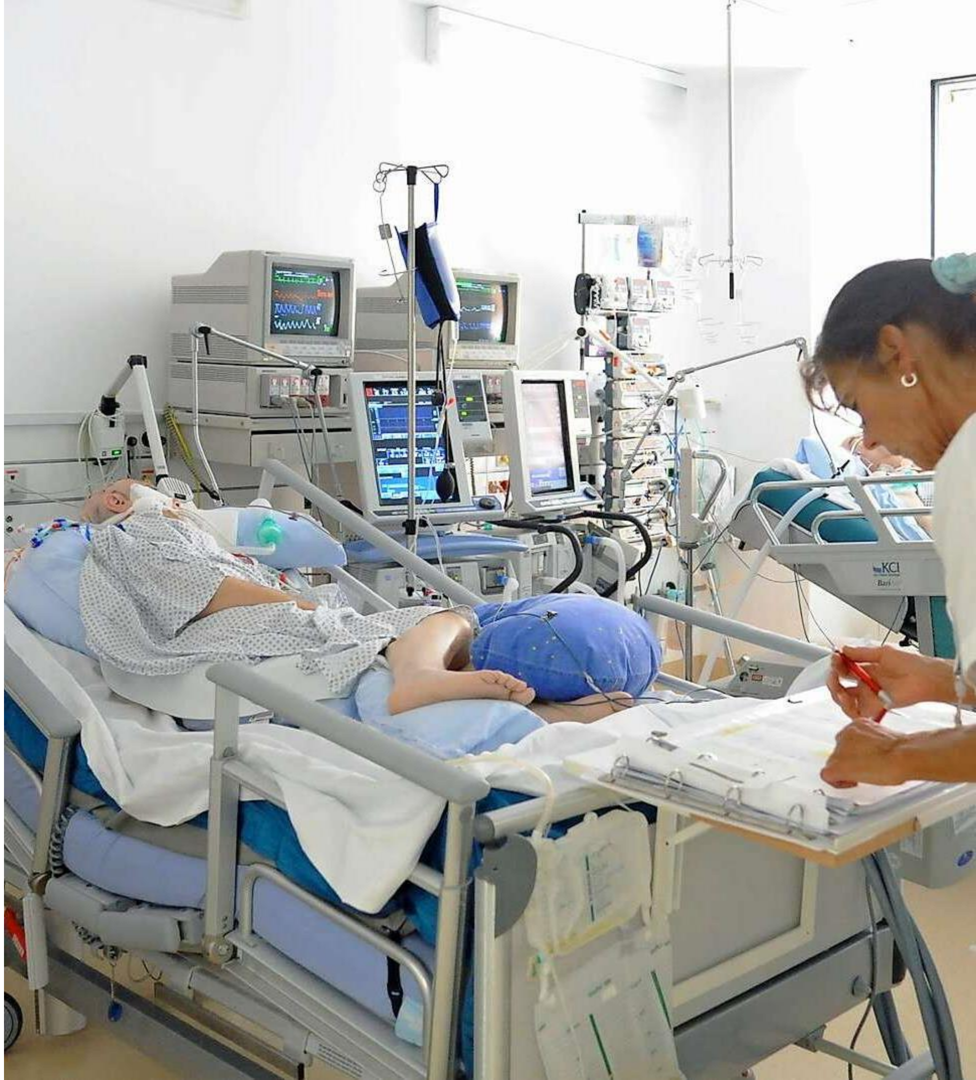

$$\begin{array}{r} Number\ of\ units \\ started\ to\ get \\ Q\ good\ units \end{array} = \frac{Q}{Process\ yield}$$

Analogous calculation to determine the capacity of each resource in the process so that the desired output is achieved.

# REWORK

# Cardiac Intensive Care Unit (CICU)

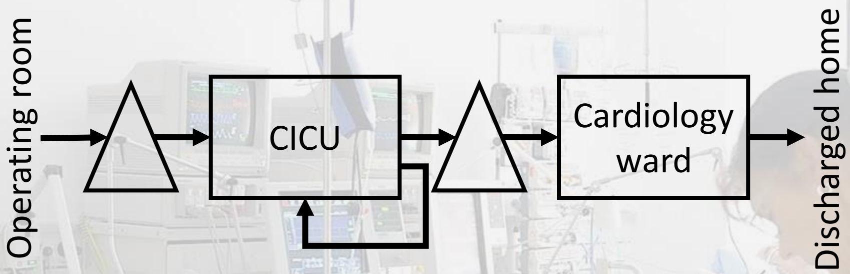
- Specialized hospital wards dedicated to caring for people with serious or acute heart problems.
- Staffed around the clock by nurses, technicians, and physicians specially trained.
- Specialized equipment for cardiac monitoring, testing and treatment.



# CICU Challenges

- How to find the bottleneck and the capacity in a process with rework?

**CICU Process Flow Diagram**




**CICU Data**

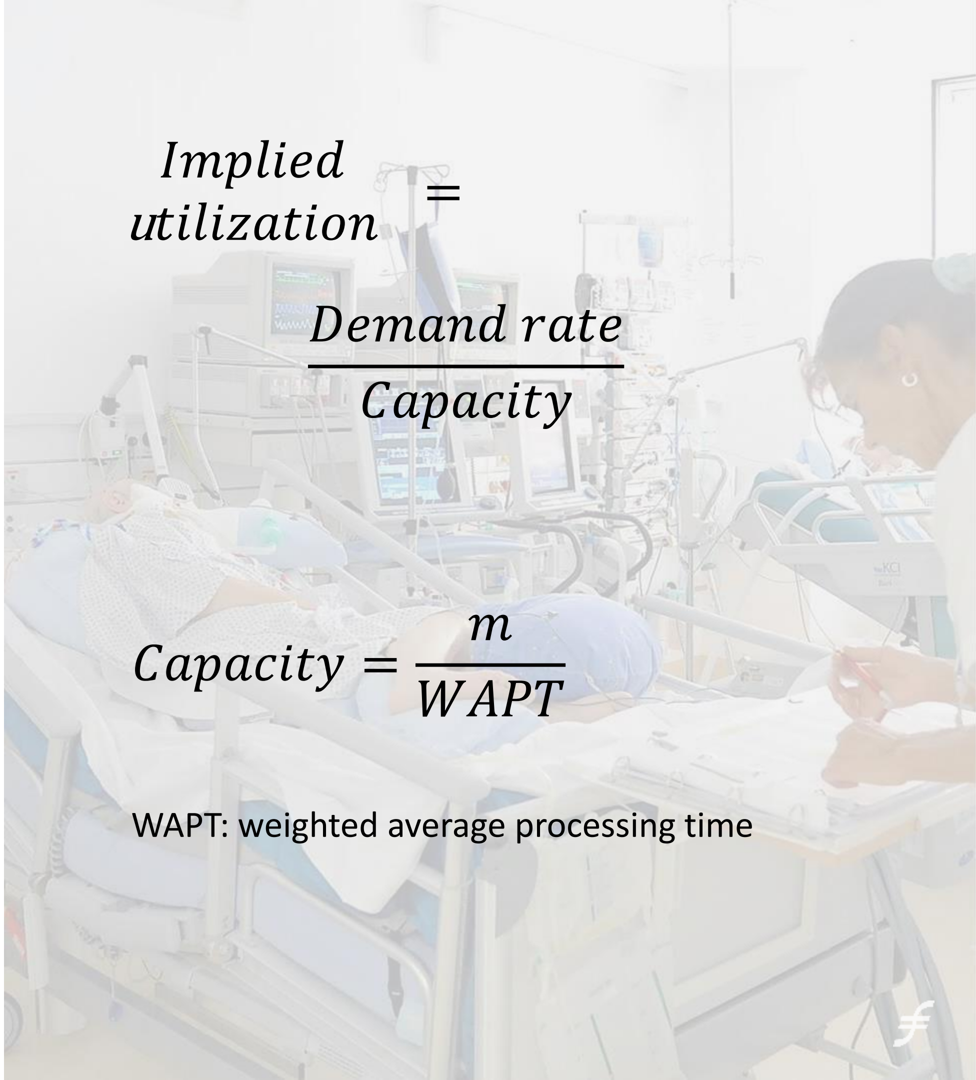
- 12 beds in the CICU, 18 beds in the cardiology ward.
- Patients are admitted to the CICU at the rate of 1.2 patients per day.
- Patients without complications stay for 5 days.
- Patients developing a complication (20%) stay for 13 days.
- Patients discharged from CICU to the cardiology ward spend there four days.
- No rework of rework.

# Defining the Average Patient as Flow Unit

Calculation of weighted average processing times:

$$WAPT_{CICU} =$$

$$WAPT_{Ward} =$$



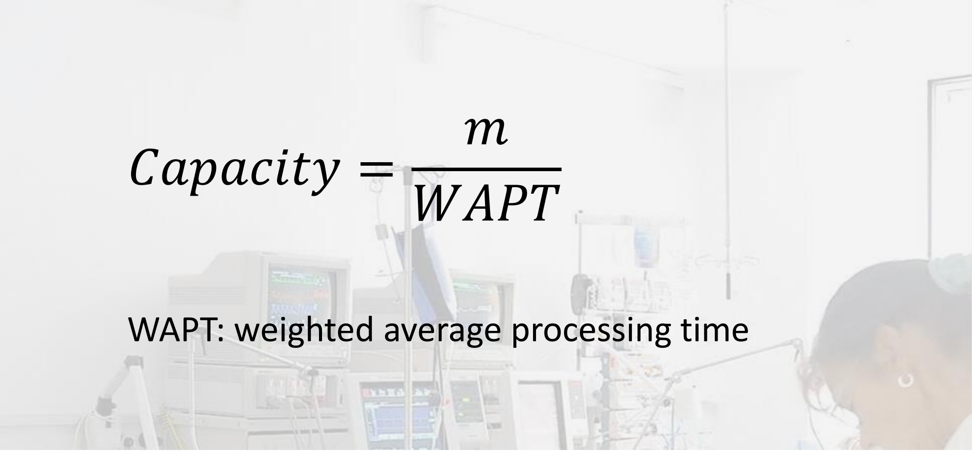
$$\begin{matrix} Implied \\ utilization \end{matrix} = \frac{Demand\ rate}{Capacity}$$

$$Capacity = \frac{m}{WAPT}$$

WAPT: weighted average processing time

# Capacities

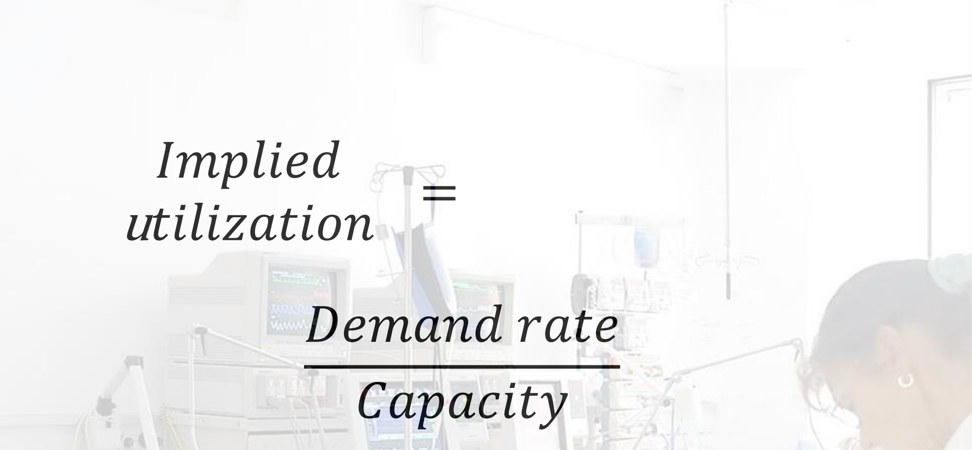
Calculation of capacities:



$$Capacity = \frac{m}{WAPT}$$

WAPT: weighted average processing time

# Implied utilization and bottleneck



$$\text{Implied utilization} = \frac{\text{Demand rate}}{\text{Capacity}}$$

Calculation of implied utilizations (iu):

The bottleneck in the process is CICU, not Ward.

# How to find the bottleneck and the capacity in a process with rework?

- Step 1
  At each resource with rework, evaluate the weighted average processing time.
- Step 2
  Evaluate the capacity of each resource using the formula:

$$Capacity = \frac{m}{WAPT}$$

- Step 3
  Evaluate for each resource the implied utilization:

$$\begin{matrix} Implied \\ utilization \end{matrix} = \frac{Demand\ rate}{Capacity}$$

- The resource with the highest implied utilization is the bottleneck.

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# 2023 Operations Management

# PROCESS INTERRUPTIONS

# PRODUCTION CYCLES DURING PROCESS INTERRUPTIONS

# Xootr Component Production

- Two components for a Xootr are made with a CNC milling machine:
  - Steer support
  - Metal rib
- Bill of material: each Xootr needs one steer support and two ribs (that is also called one component set).
- Xootr LLC has a single milling machine.



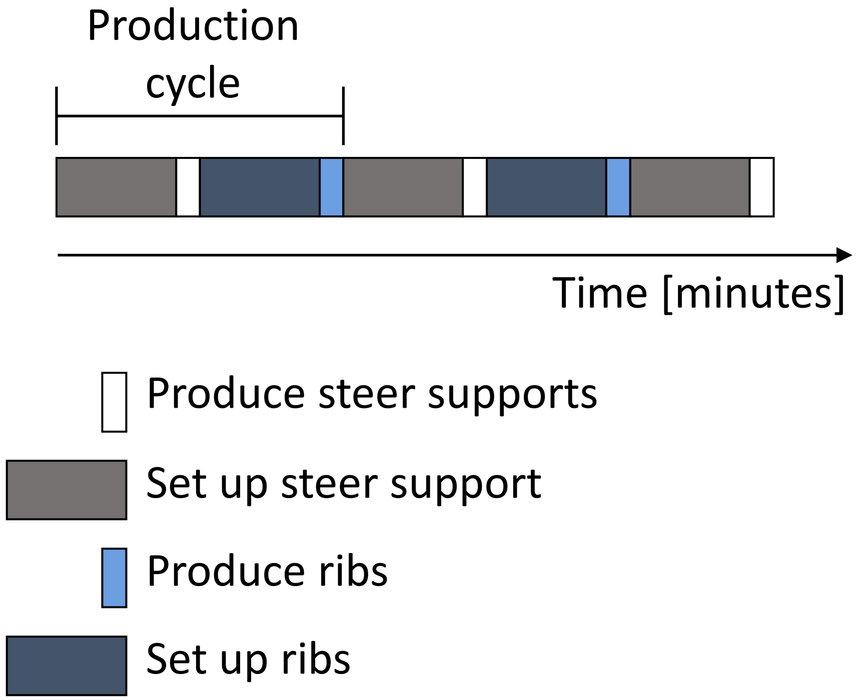

https://www.xootr.com/

# Milling Machine Setup and Production

- First step to produce a part: set up the CNC milling machine
- Set up consists of:
  1. installing the correct tooling
  2. calibrating the equipment to the correct dimensions
- Set up time: 60 minutes (not dependent on the part produced)
- Set up time is non-value adding

- Once the milling machine is set up, it can make the parts quickly
- Production rates
  - Steer supports: 1 unit/minute
  - Ribs: 2 units/minute

# Production Cycle of the Milling Machine




- A production cycle is a repeating sequence of produced units.
- To evaluate capacity, we must define the flow unit:
  - one Xootr, or, equivalently,

  Or
  - one component set (consisting of 1 steer support and 2 ribs needed per Xootr)
- The batch size is the number of flow units produced in one cycle.
  - For example, if we produce 12 steer supports and 24 ribs in a production cycle, such that we can produce 12 Xootrs, the batch size is said to be 12 component sets.

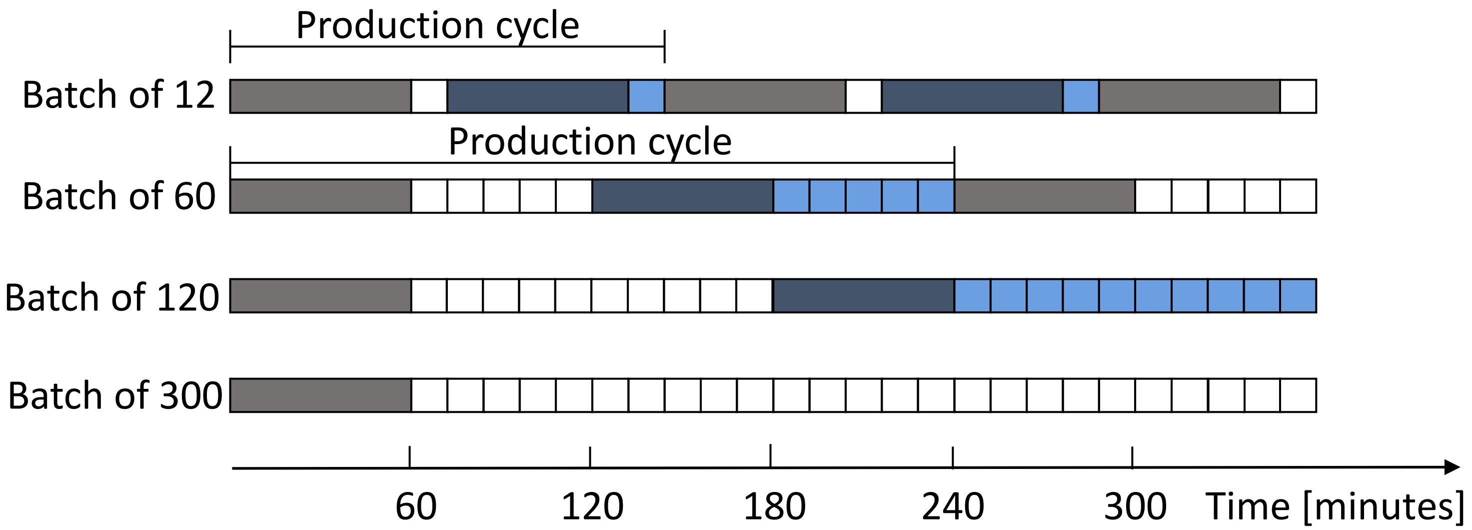
# SETUPS AND CAPACITY

# Xootr Component Production Challenges

- What is the capacity of the milling machine?
- What is the utilization of the milling machine?
- What is the average/maximum inventory of ribs and steer supports?
- What batch size minimizes inventory while not constraining the flow through the process?


https://www.xootr.com/

# The Impact of Batch Size on Capacity – What is Your Intuition?




- Produce steer supports (1 box corresponds to 12 units = 12 scooters)
- Set up steer support
- Produce ribs (1 box corresponds to 24 units = 12 scooters)
- Set up ribs

# Capacity of a Resource with Setups

- So far, we defined capacity as (Topic 3):

$$Capacity = \frac{m}{Processing\ time} = \frac{Units\ produced}{Time\ to\ produce\ the\ units}$$

- For batch processes with setups, the time to produce a batch is given by:

$$Time\ to\ produce\ a\ batch = Setup\ time + Batch\ size \cdot Processing\ time$$

  where the batch size is the number of flow units produced in one “cycle”.

- Thus, the capacity of a resource with setups is:

$$Capacity = \frac{Batch\ size}{Total\ setup\ time + \ (Processing\ time \cdot Batch\ size)}$$

  where total setup time is the sum of all setup times in one “cycle”.

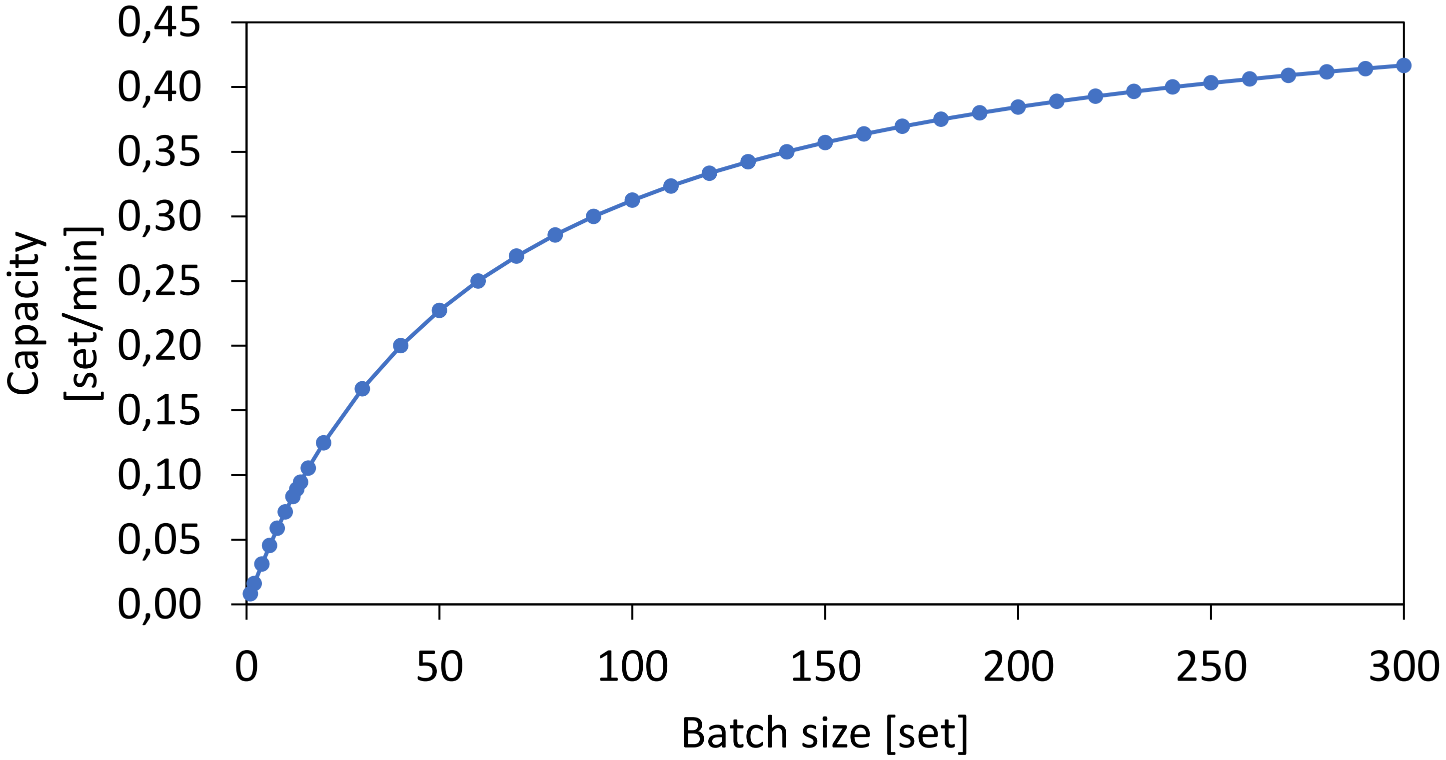
# Capacity of the Milling Machine

- Using a batch size of 100 component sets, capacity is:

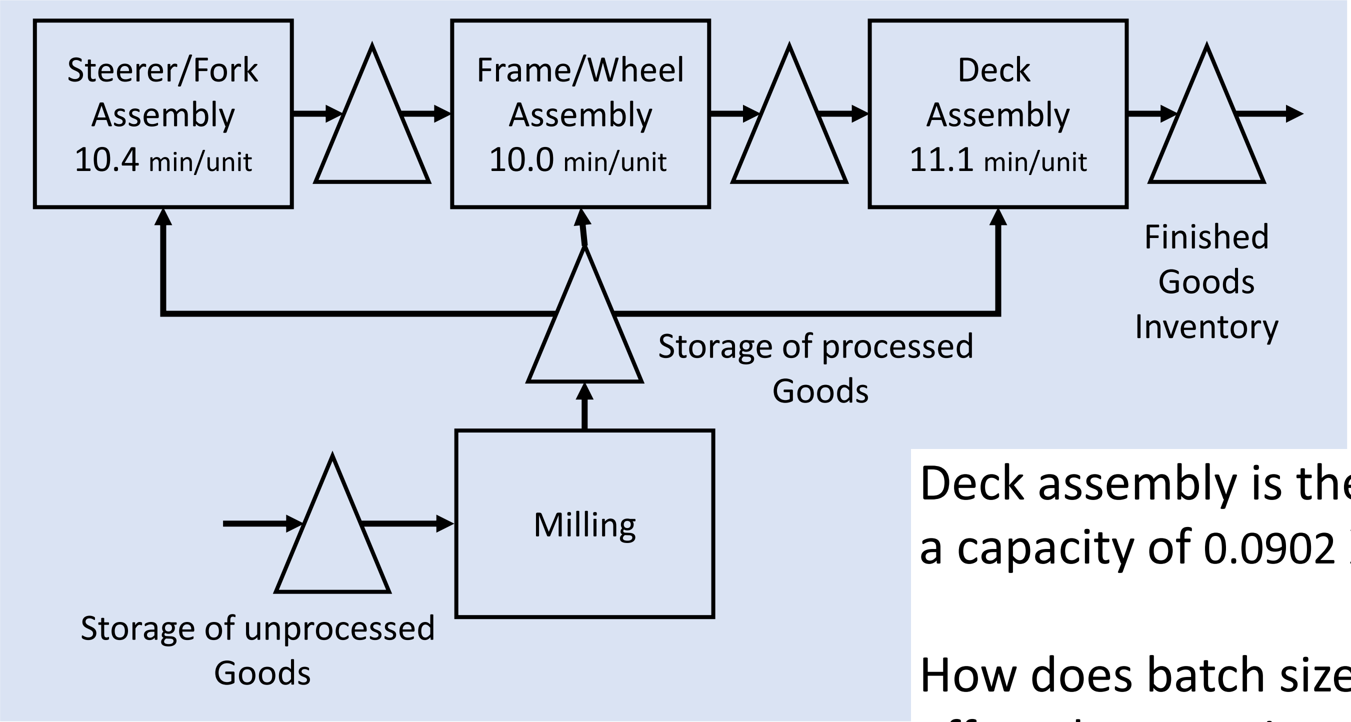
$$Capacity = \frac{Batch\ size}{Total\ setup\ time +\ (Processing\ time \cdot Batch\ size)}$$

- Total setup time (sum of all setup times in the cycle):
- Processing time per component set:
- Capacity:

# Relation of Milling Machine Capacity and Batch Size



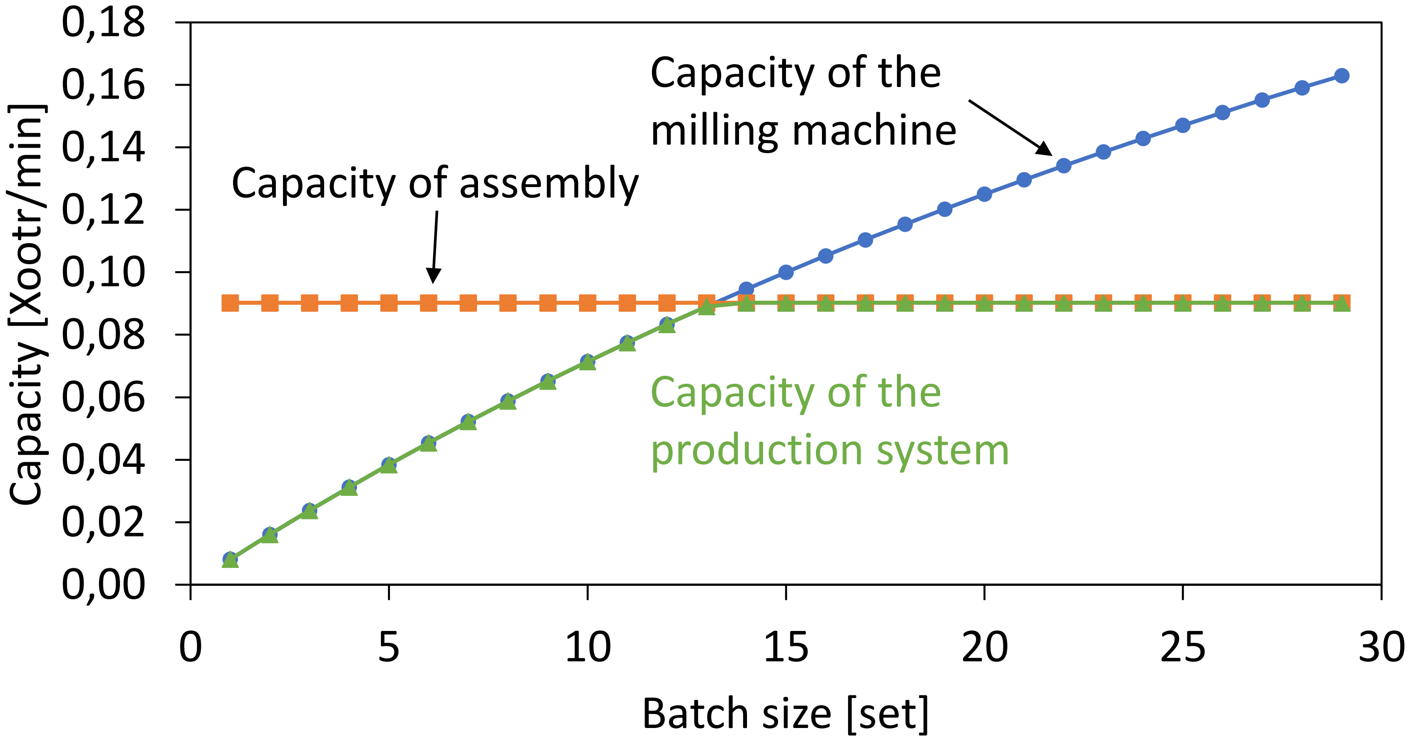
# Xootr Milling and Assembly




Deck assembly is the bottleneck with a capacity of 0.0902 Xootr per min.

How does batch size variations at milling affect the capacity of the production system?

# Capacity of the System



# Xootr Component Production Challenges

- What is the capacity of the milling machine?
- **What is the utilization of the milling machine?**
- What is the average/maximum inventory of ribs and steer supports?
- What batch size minimizes inventory while not constraining the flow through the process?




https://www.xootr.com/

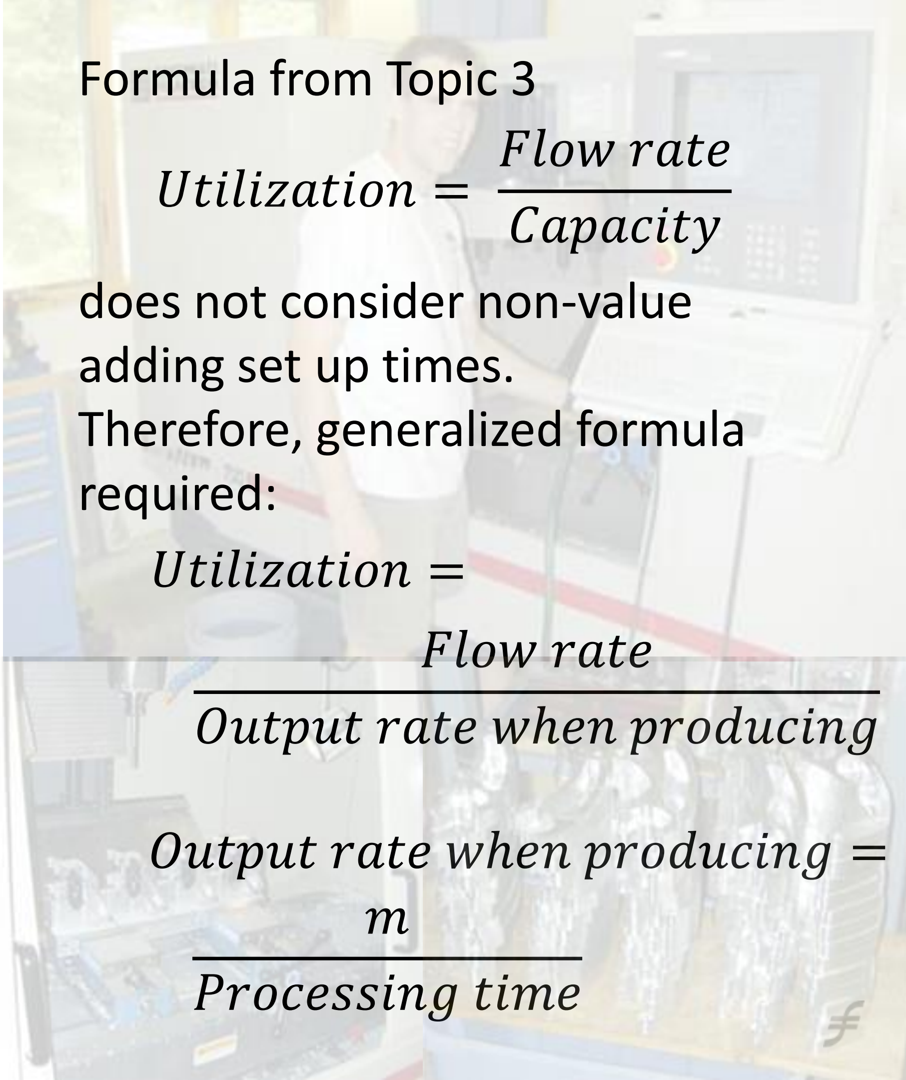
# Utilization of the Milling Machine

Assuming a capacity-constrained process, the flow rate at a batch size of 100 sets is

$$Flow\ rate =$$

$$\begin{array}{c} Output \\ rate\ when \\ producing \end{array} =$$

$$Utilization =$$



Formula from Topic 3

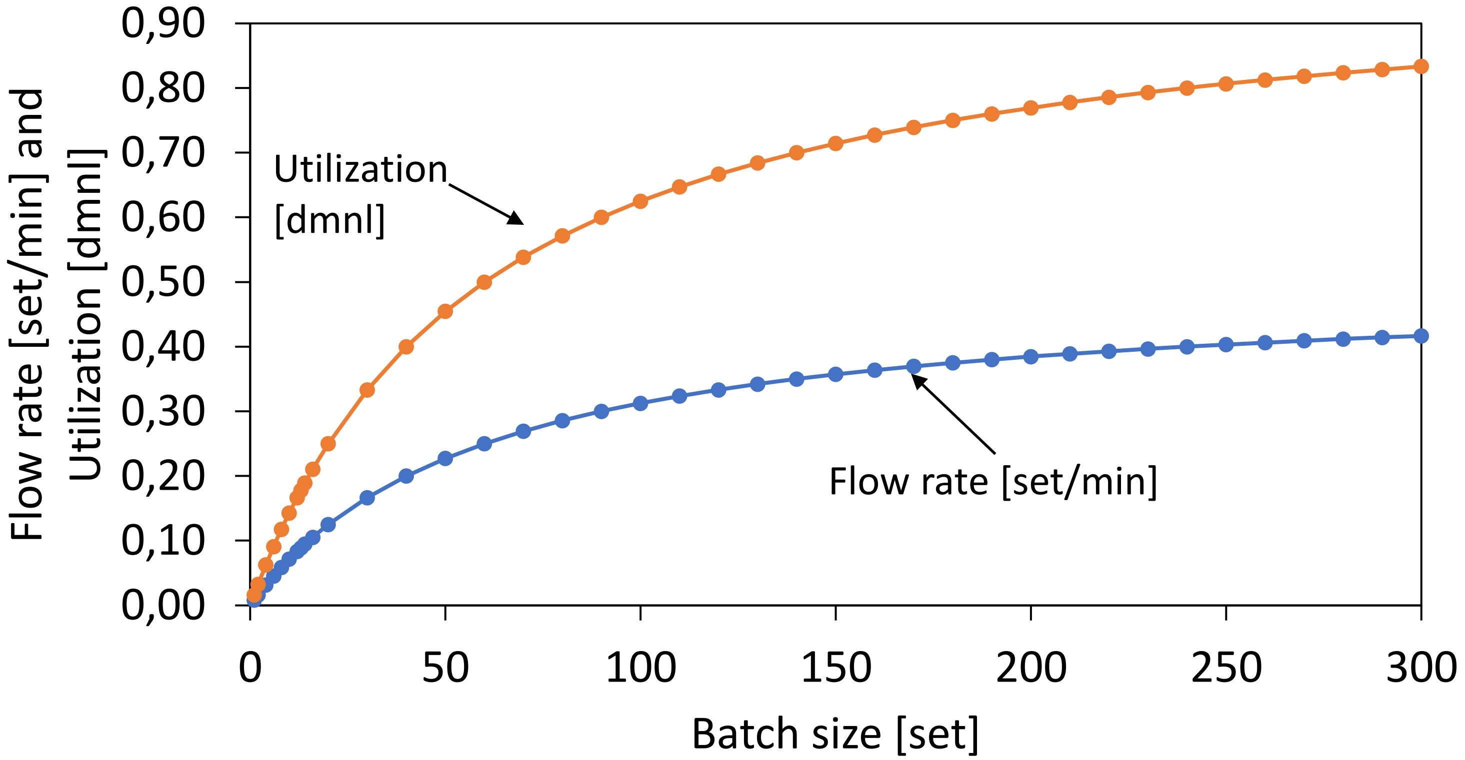
$$Utilization = \frac{Flow\ rate}{Capacity}$$

does not consider non-value adding set up times. Therefore, generalized formula required:

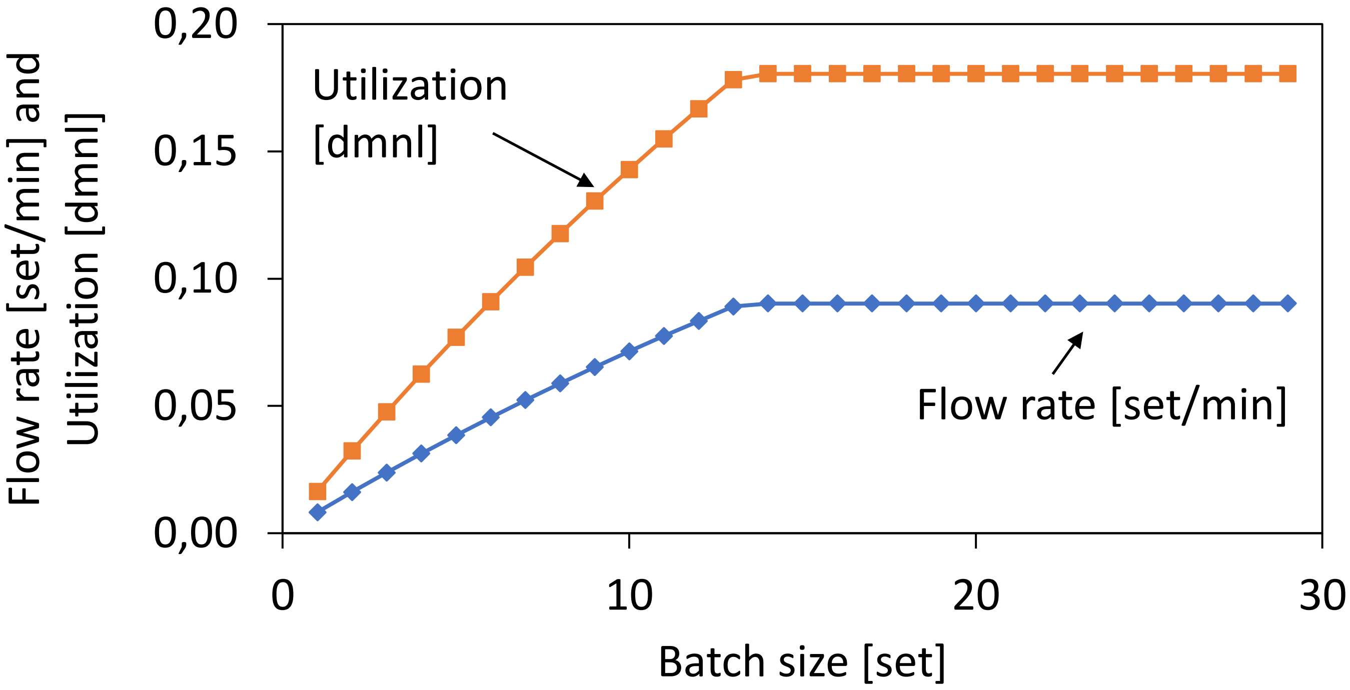
$$Utilization = \frac{Flow\ rate}{Output\ rate\ when\ producing}$$

$$Output\ rate\ when\ producing = \frac{m}{Processing\ time}$$

# Flow Rate and Utilization as a Function of Batch Size



# The Production System Perspective (Assembly Included)



# SETUPS AND INVENTORY

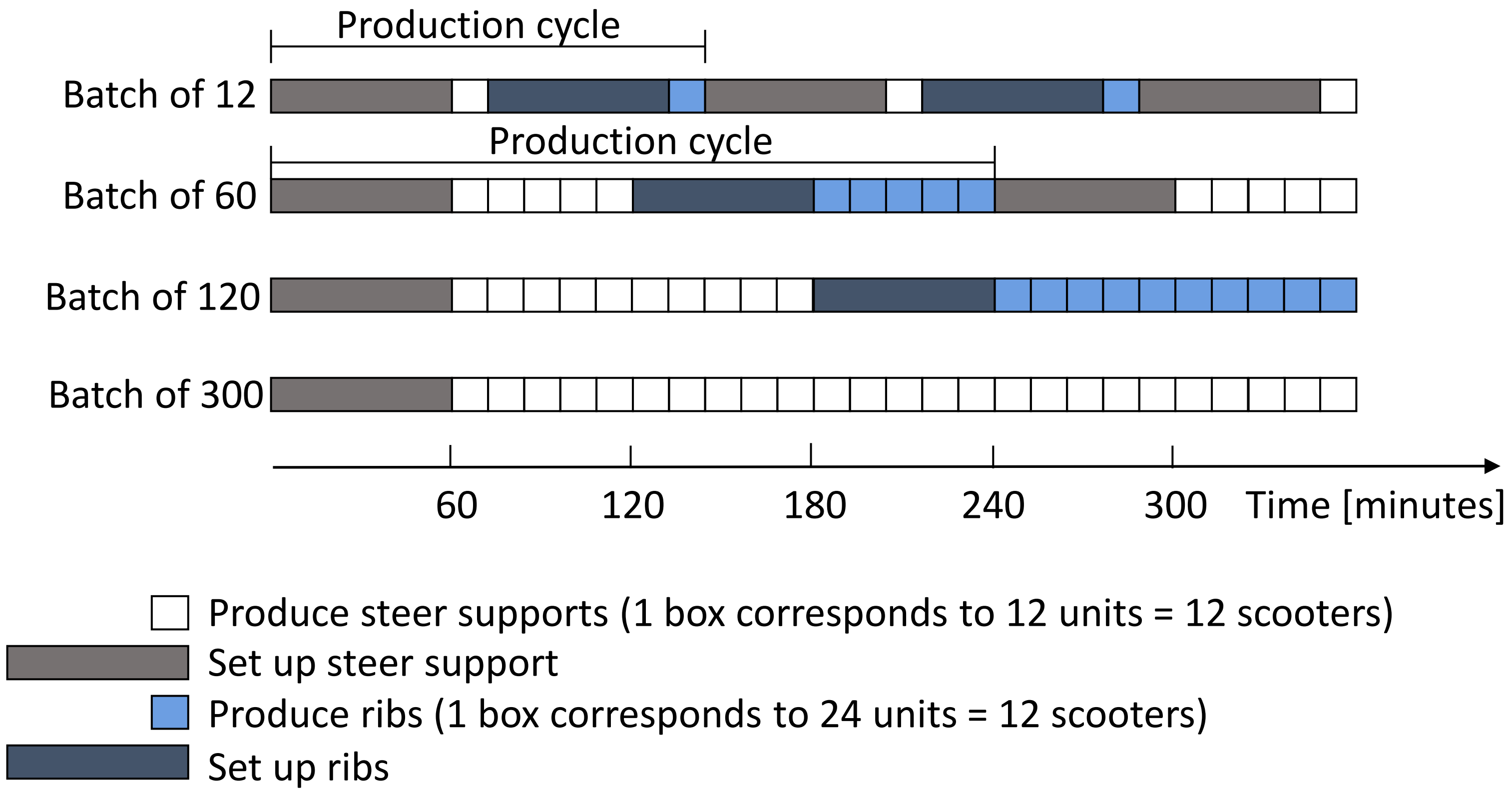
# Xootr Component Production Challenges

- What is the capacity of the milling machine?
- What is the utilization of the milling machine?
- **What is the average/maximum inventory of ribs and steer supports?**
- What batch size minimizes inventory while not constraining the flow through the process?




https://www.xootr.com/

# The Impact of Batch Size on Inventory – What is Your Intuition?

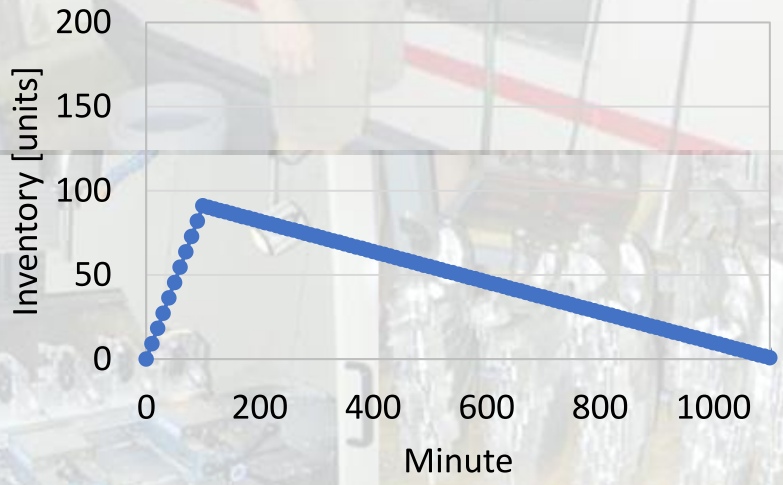


# Maximum Inventory Steer Support

- Steer support inventory net increase rate when producing:

- Time to produce one batch:

Set-up time: 60 minutes
Processing times
Steer support: 1 min/unit
Rib: 0.5 min/unit
Assembly capacity: 0.0902 Xootr per min
Batch size: 100 component sets



# Maximum Inventory Steer Support

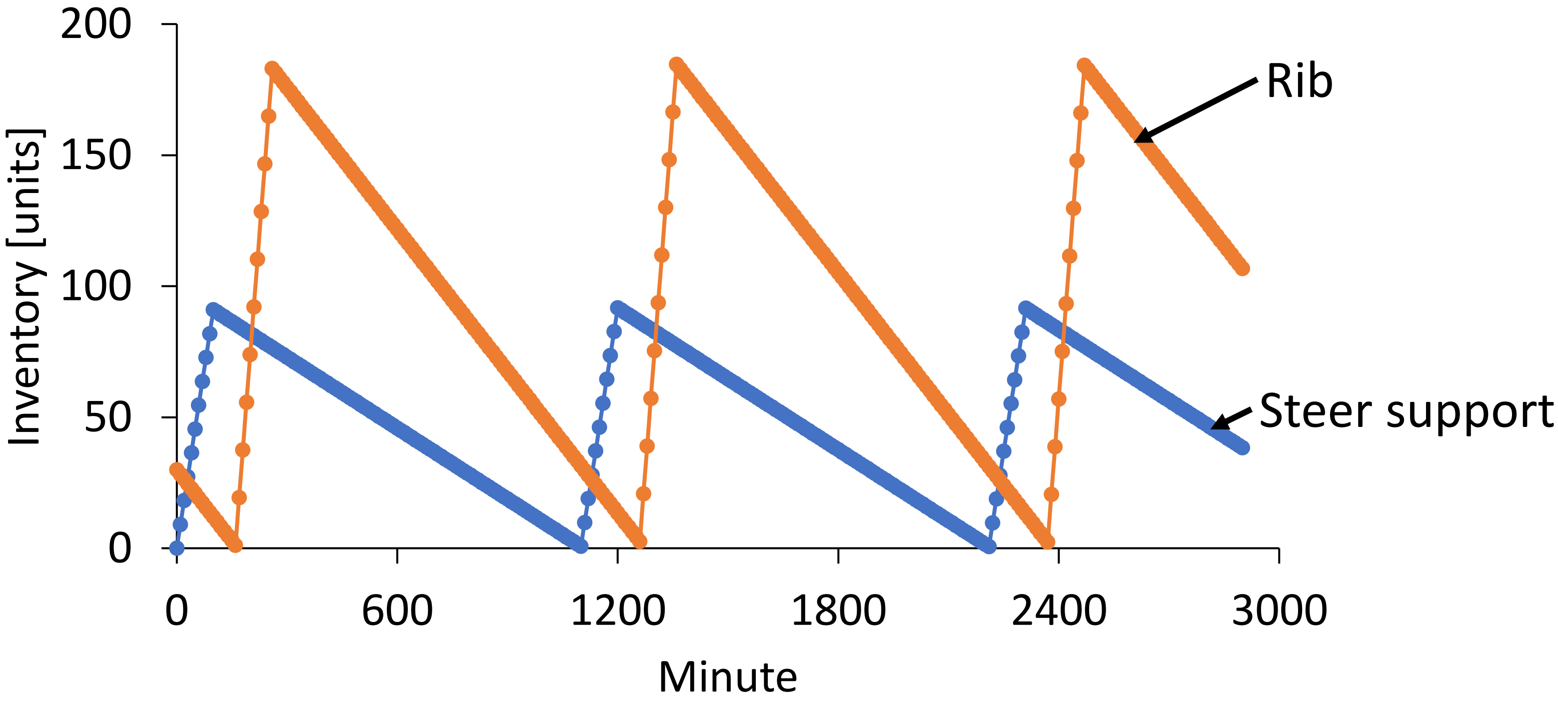
$$Maximum\ inventory$$

$$= Batch\ size \cdot Processing\ time \left( \frac{1}{Processing\ time} - Flow\ rate \right)$$

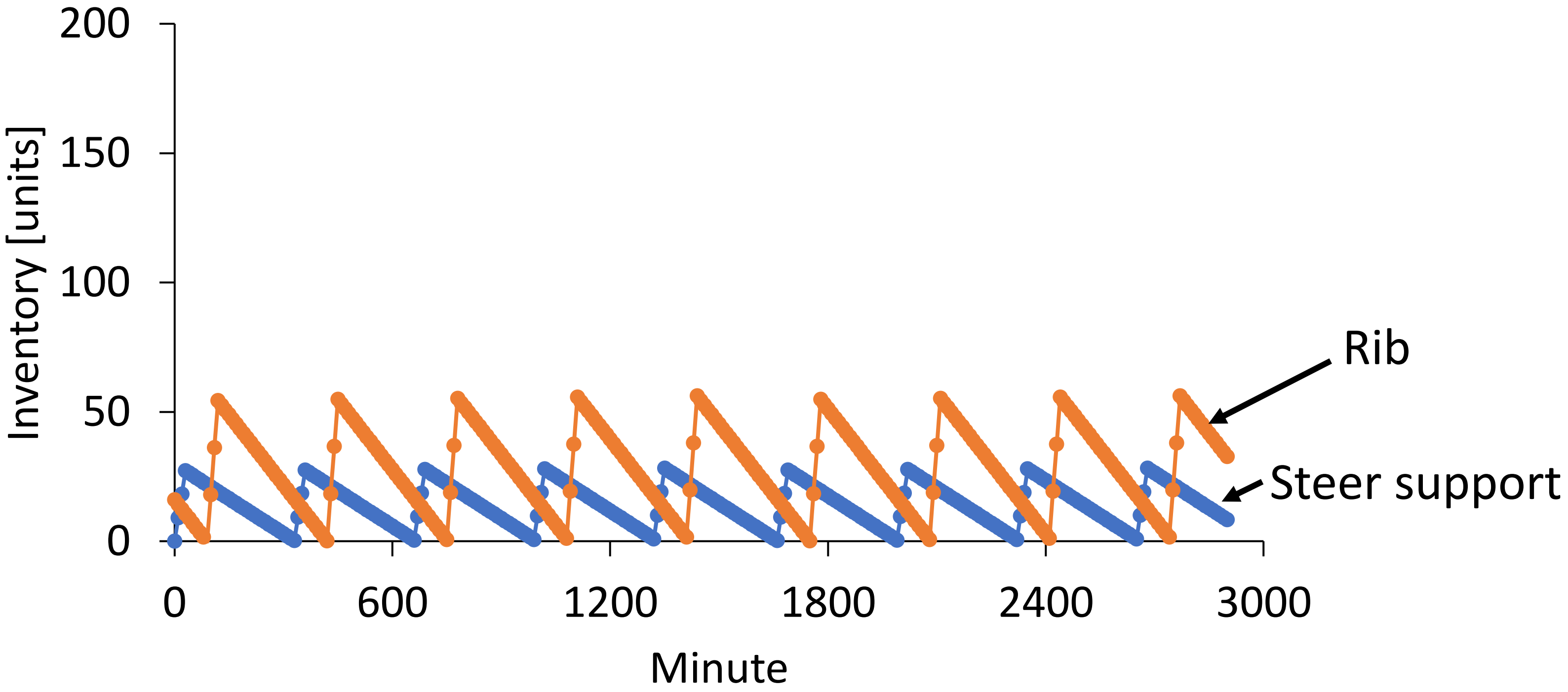
$$= Batch\ size \cdot [1 - (Flow\ rate \cdot Processing\ time)]$$

$$Maximum\ inventory\ steer\ support$$

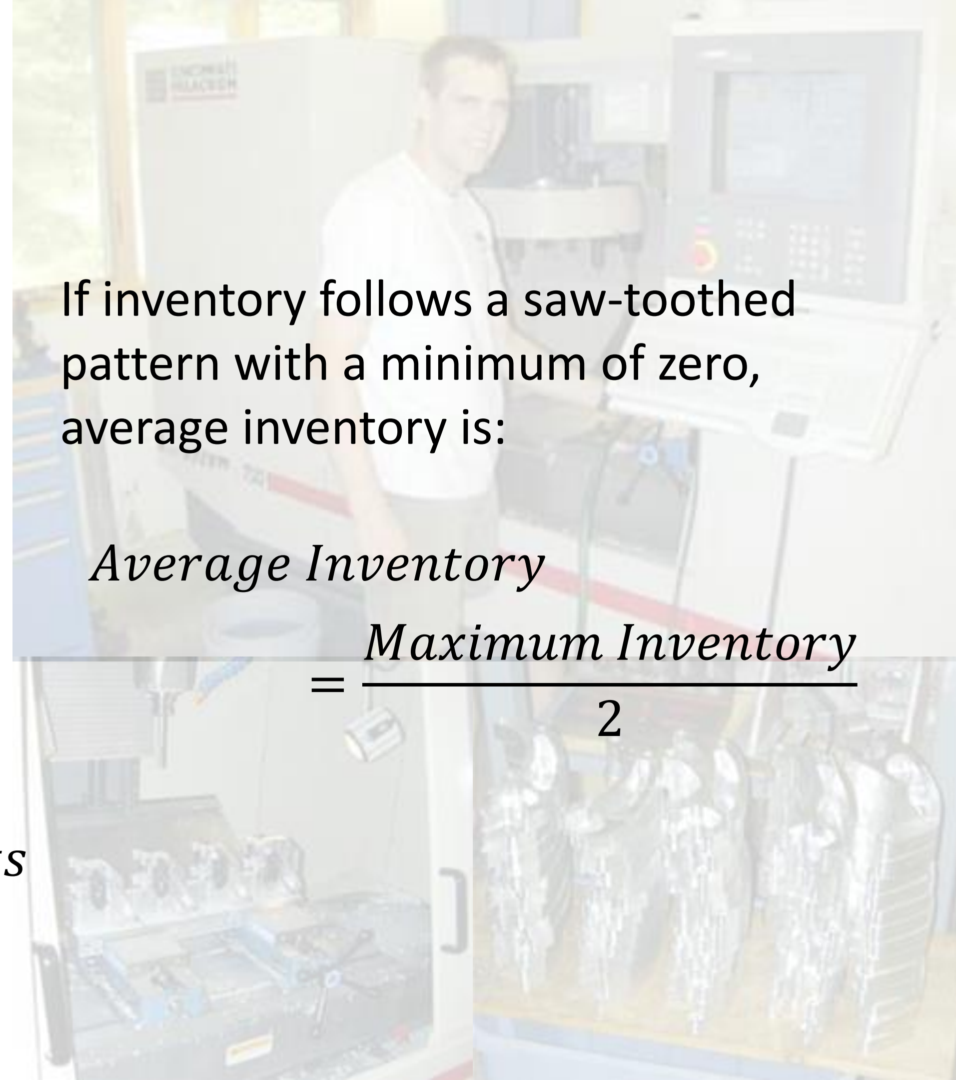
# Inventory Over Time (Batch Size = 100)



# Inventory Over Time (Batch Size = 30)



# Average Inventory



- Steer support (Batch size 100 or 30)

$$= \frac{90.9774\,units}{2} = 45.4887\,units$$

$$= \frac{27.2932\,units}{2} = 13.6466\,units$$

- Ribs (Batch size 100 or 30)

$$= \frac{181.\,9549\,units}{2} = 90.9774\,units$$

$$= \frac{54.5864\,units}{2} = 27.\,2932\,units$$

If inventory follows a saw-toothed pattern with a minimum of zero, average inventory is:

$$Average\ Inventory = \frac{Maximum\ Inventory}{2}$$

# RECOMMENDED BATCH SIZE

# Xootr Component Production Challenges

- What is the capacity of the milling machine?
- What is the utilization of the milling machine?
- What is the average/maximum inventory of ribs and steer supports?
- **What batch size minimizes inventory while not constraining the flow through the process?**

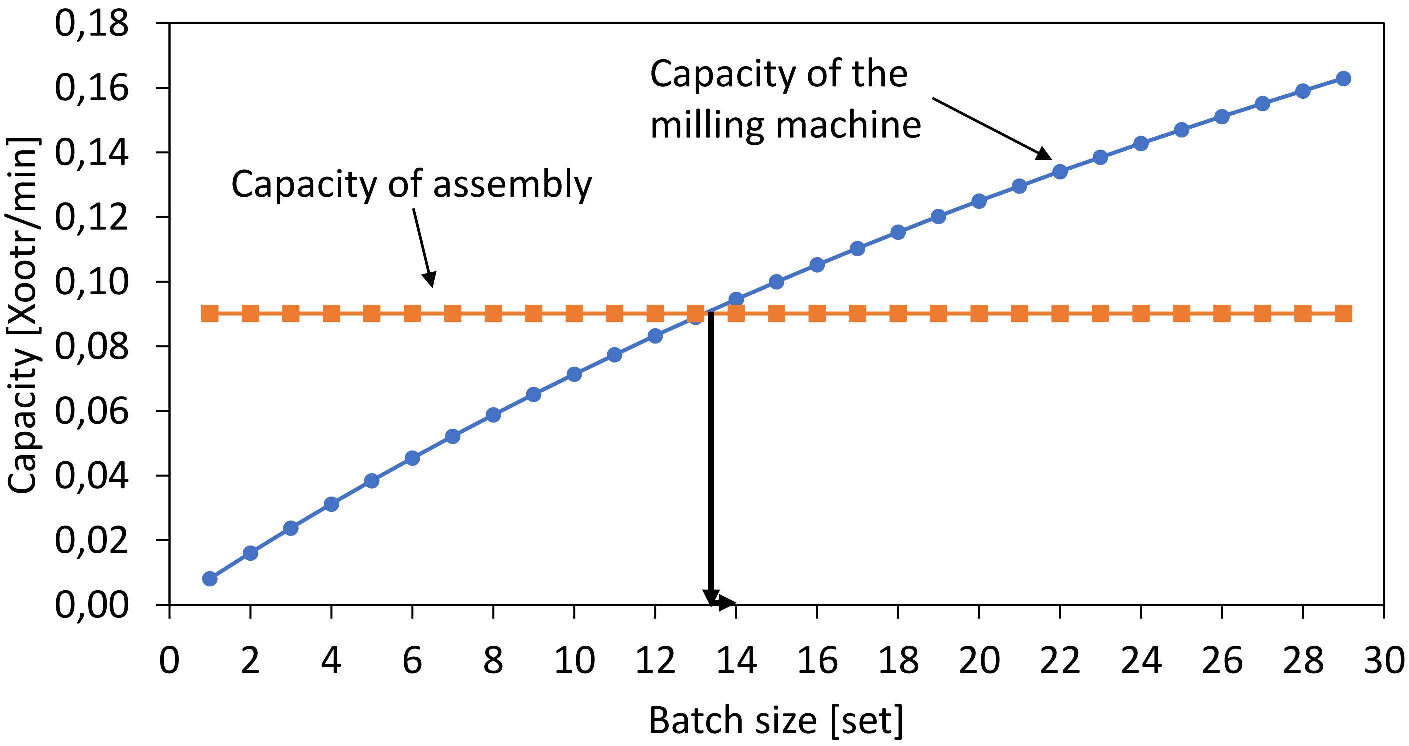



https://www.xootr.com/

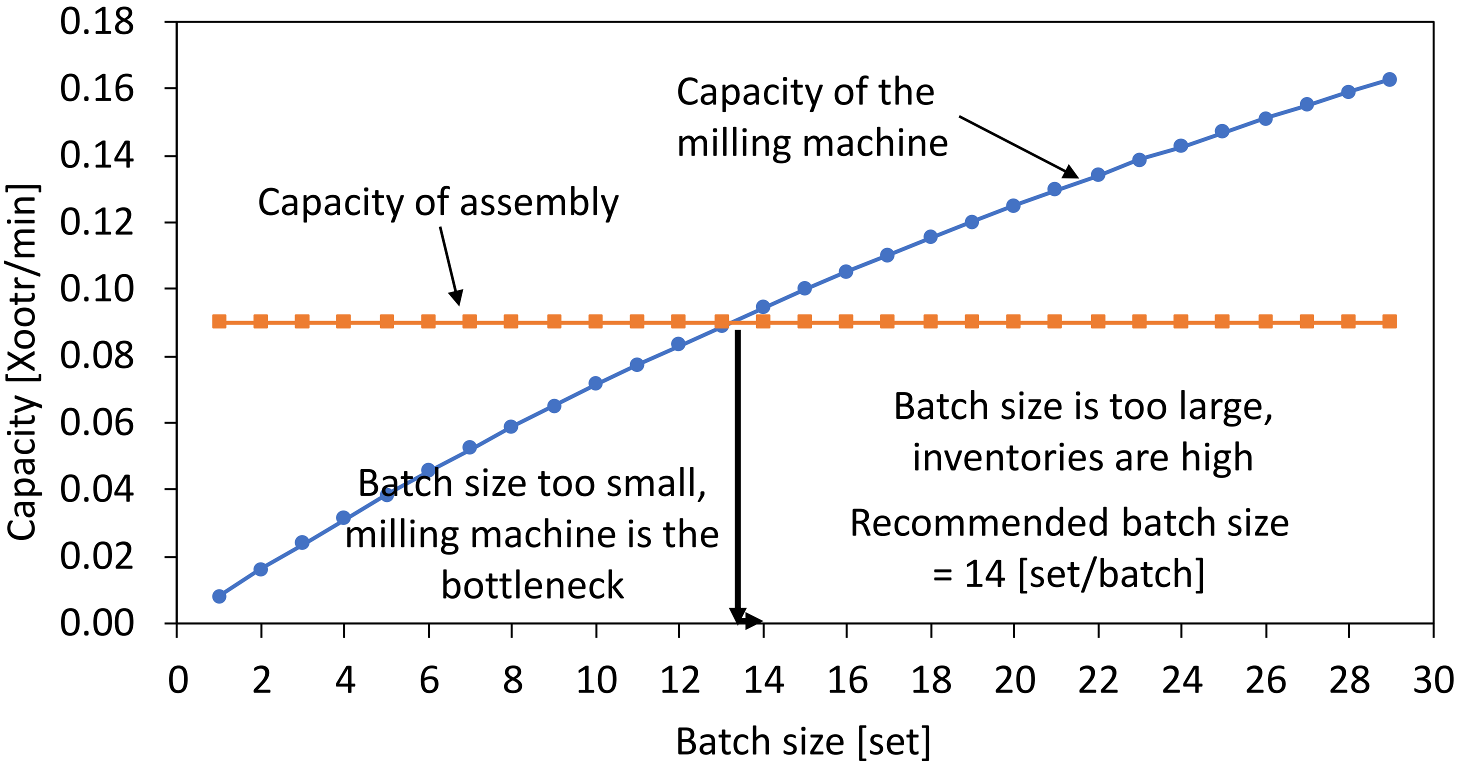
# Choosing a Batch Size in a Process with Setups

- Conflicting objectives
  - Large batches ⇨ large inventory, but gains in capacity.
  - Small batches ⇨ small inventory, but losses in capacity.
- Important observation
  - Capacity at the bottleneck resource is extremely valuable (in a capacity-constrained process).
  - Capacity at a non-bottleneck resource is free (assuming that costs related to this resource are fixed).
- Implications
  - If setup occurs at the bottleneck ⇨ increase the batch size.
  - If setup occurs at **non**-bottleneck ⇨ decrease the batch size.

# Recommended Batch Size for the Milling Machine



# Recommended Batch Size for the Milling Machine



# Choosing the Batch Size to Meet a Target Capacity

- Start with the capacity equation:

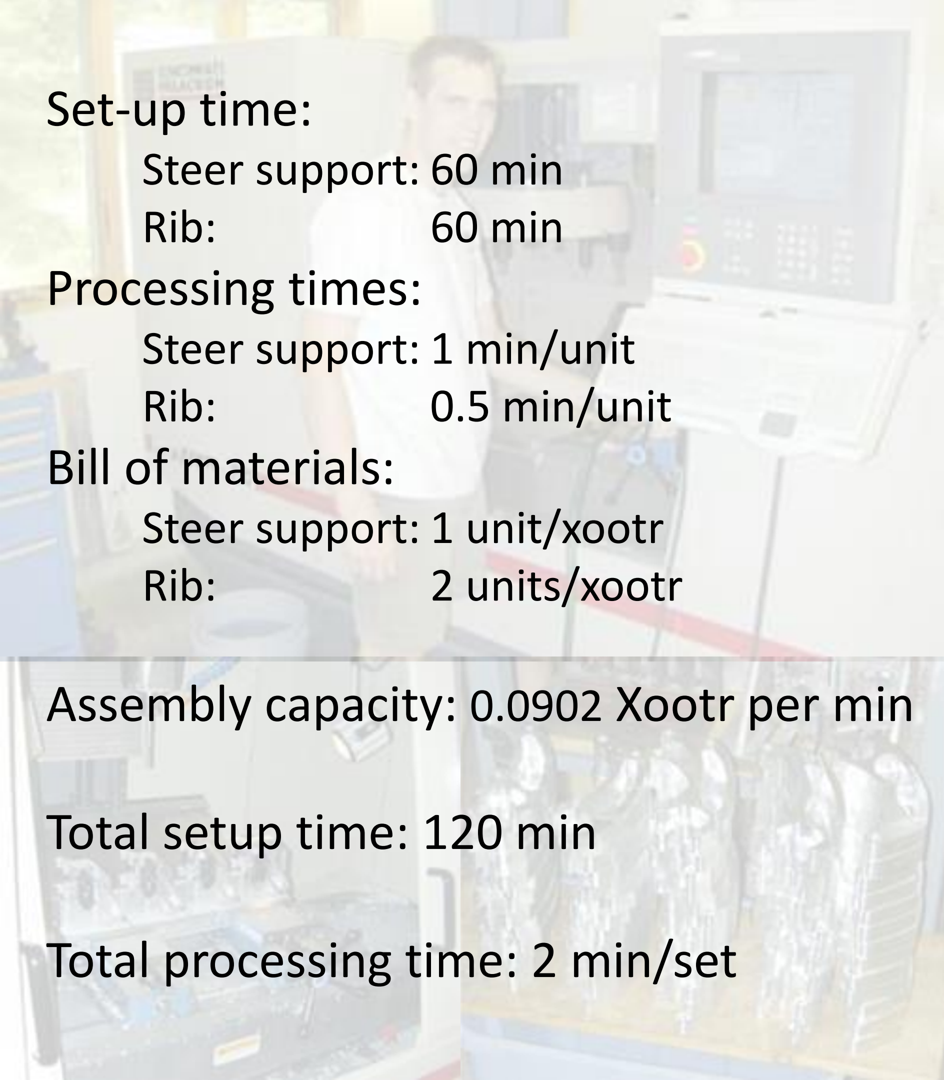
$$Capacity = \frac{Batch\ size}{Total\ setup\ time + \ (Processing\ time \cdot Batch\ size)}$$

- Understand capacity as target capacity and set it equal to the flow rate .
- Rearrange the above equation to yield an equation for the recommended batch size:

$$Recommended\ batch\ size = \frac{Target\ capacity \cdot Total\ setup\ time}{1 - \ (Target\ capacity \cdot Processing\ time)}$$

# Recommended Batch Size

- Recommended batch size (in component sets):



Set-up time:

| | |
|---|---|
| Steer support: | 60 min |
| Rib: | 60 min |

Processing times:

| | |
|---|---|
| Steer support: | 1 min/unit |
| Rib: | 0.5 min/unit |

Bill of materials:

| | |
|---|---|
| Steer support: | 1 unit/xootr |
| Rib: | 2 units/xootr |

Assembly capacity: 0.0902 Xootr per min

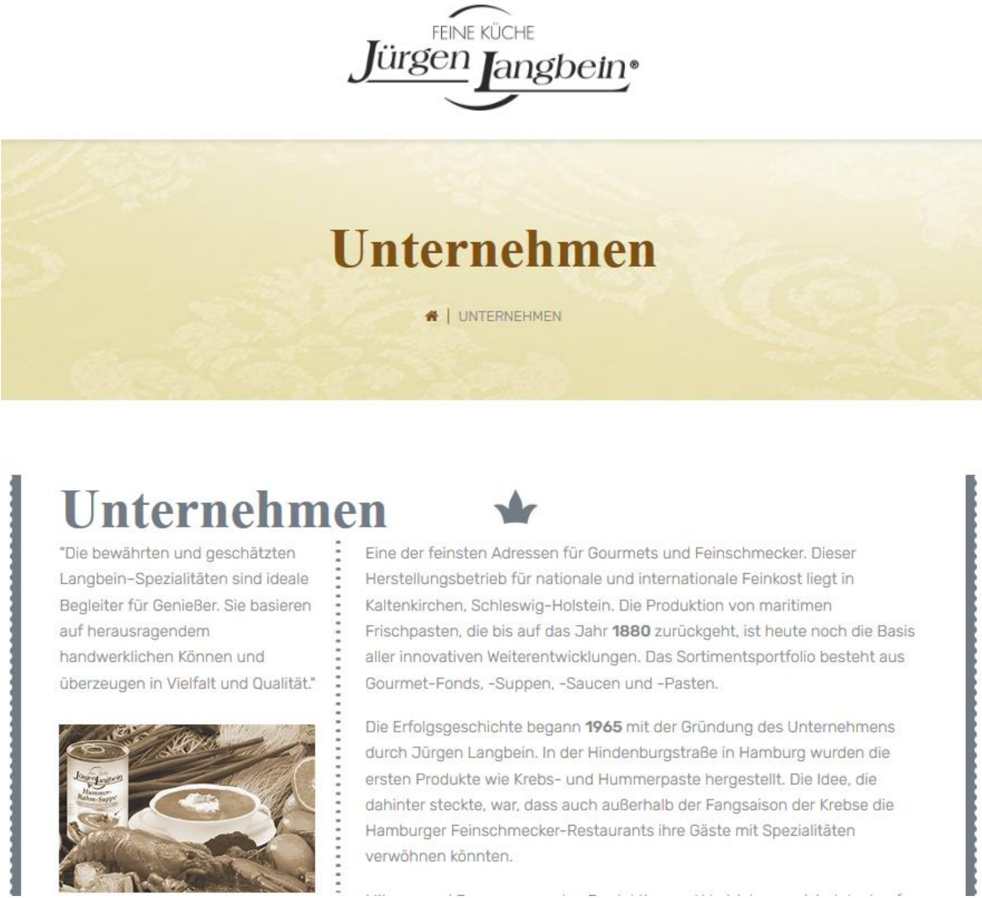
Total setup time: 120 min

Total processing time: 2 min/set

# PRODUCT VARIETY

# Jürgen Langbein

- Founded 1965 in Hamburg
- Production of fonds, soups, sauces, and pastes
- 3000m² factory
- Typical size of kettle: 400 l



FEINE KÜCHE Jürgen Langbein®

Unternehmen

UNTERNEHMEN

Unternehmen

"Die bewährten und geschätzten Langbein-Spezialitäten sind ideale Begleiter für Genießer. Sie basieren auf herausragendem handwerklichen Können und überzeugen in Vielfalt und Qualität."

Eine der feinsten Adressen für Gourmets und Feinschmecker. Dieser Herstellungsbetrieb für nationale und internationale Feinkost liegt in Kaltenkirchen, Schleswig-Holstein. Die Produktion von maritimen Frischpasten, die bis auf das Jahr **1880** zurückgeht, ist heute noch die Basis aller innovativen Weiterentwicklungen. Das Sortimentsportfolio besteht aus Gourmet-Fonds, -Suppen, -Saucen und -Pasten.

Die Erfolgsgeschichte begann **1965** mit der Gründung des Unternehmens durch Jürgen Langbein. In der Hindenburgstraße in Hamburg wurden die ersten Produkte wie Krebs- und Hummerpaste hergestellt. Die Idee, die dahinter steckte, war, dass auch außerhalb der Fangsaison der Krebse die Hamburger Feinschmecker-Restaurants ihre Gäste mit Spezialitäten verwöhnen könnten.

https://www.langbein.de/unternehmen.html

# Jürgen Langbein Soup Production Challenge

- What impact has product variety in processes with set-ups on process performance?
- Which strategies are available?




https://www.langbein.de/unternehmen.html

# Setup Time and Product Variety: Two Soups

- Consider a process that makes two kinds of soup.
- Define the flow unit to be one liter of soup.
- Assume we iterate between vegetable and tomato production.
- Define the batch to be the total quantity (in liter) of vegetable and tomato soup.
- What batch size minimizes inventory?


| | Vegetable | Tomato |
|---|---|---|
| Demand [l/h] | 100 | 75 |
| Setup time [h] | 0.4 | 0.4 |
| Production rate [l/h] | 300 | 300 |

# Two Soup Analysis

- Our target capacity (or flow rate) is 100 + 75 = 175 liter per hour.
- Each batch involves producing vegetable **and** tomato soup, so the total setup time is 2 x 0.4 = 0.8 hour per batch.
- Processing time = 1/300 hour per liter.
- Recommended batch size:
- Production:

# Three Soups and Expanding Demand

- Process output: three types of soup (vegetable, tomato, potato)
- Now suppose one kind of soup is added and demand for the others remains the same.
- A batch is still a set of vegetable, tomato and potato soup.
- What batch size minimizes inventory?



| | Vegetable | Tomato |
|---|---|---|
| Demand [l/h] | 100 | 75 |
| Setup time [h] | 0.4 | 0.4 |
| Production rate [l/h] | 300 | 300 |

| | Potato |
|---|---|
| Demand [l/h] | 50 |
| Setup time [h] | 0.4 |
| Production rate [l/h] | 300 |

# Three Soups Expanding Demand Analysis

- Desired capacity (or flow rate) is 100 + 75 + 50 = 225 l/hour.
- Each batch involves producing vegetable, tomato and potato soup, so the total setup time is 0.4 h + 0.4 h + 0.4 h = 1.2 hours per batch.
- Processing time = 1/300 hour per liter.
- Recommended batch size:
- Production:

# Jürgen Langbein Soup Production Challenge

- What impact has product variety in processes with set-ups on process performance?
- **Which strategies are available?**

FEINE KÜCHE Jürgen Langbein®



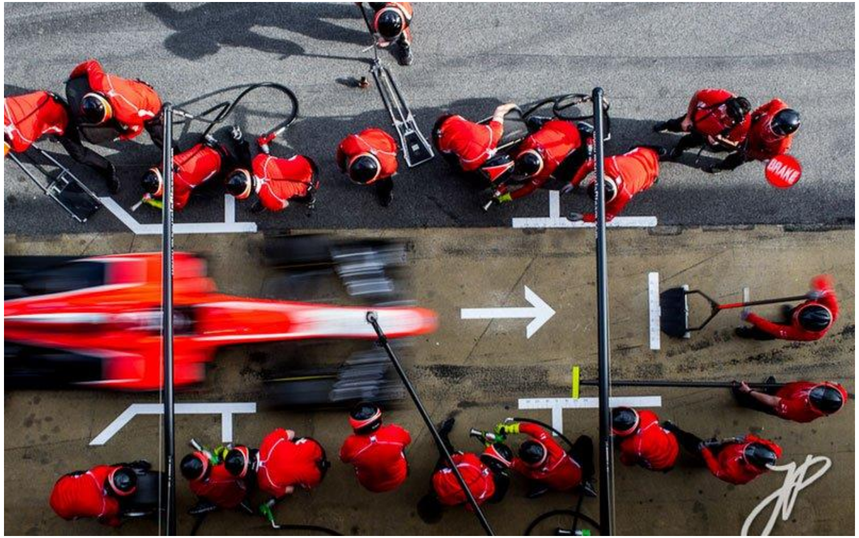

https://www.langbein.de/unternehmen.html

# Henry Ford's Famous Proclamation

*"Customers can have any color they want, as long as it is black."*

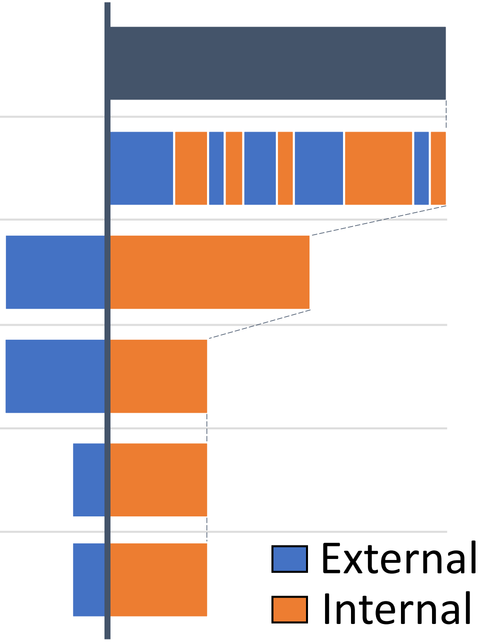
# Reduction of Set-up Time with SMED

- Single minute exchange of die (SMED) method.
- Paradigm: Setup times should take less than 10 minutes.
- Idea: Divide setup-related tasks into internal and external setup tasks.
  - Internal tasks: can only be executed while the machine is stopped.
  - External tasks: can be done while the machine is still operating, i.e., before or after the actual changeover occurs.



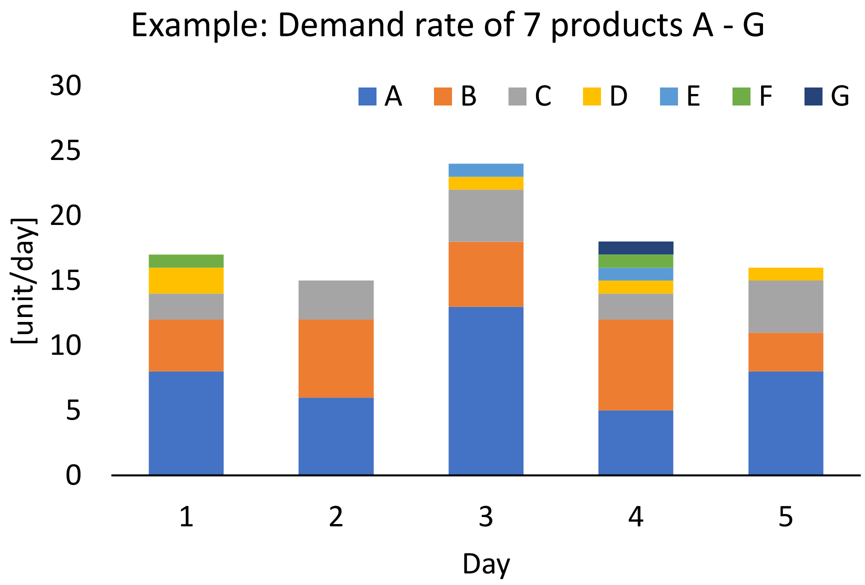
# Setup Time Reduction with the 6-stage SMED approach

| Stage | Before/after shutdown | During shutdown |
|---|---|---|
| 1 Measure total changeover time | | |
| 2 Determine internal and external activities | | |
| 3 Move external activities to before or after the shutdown | | |
| 4 Improve the internal activities | | |
| 5 Improve the external activities | | |
| 6 Standardize procedures | | |

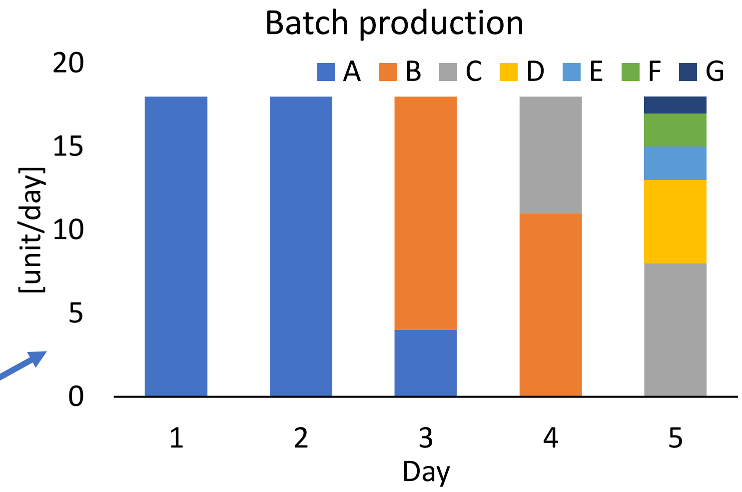


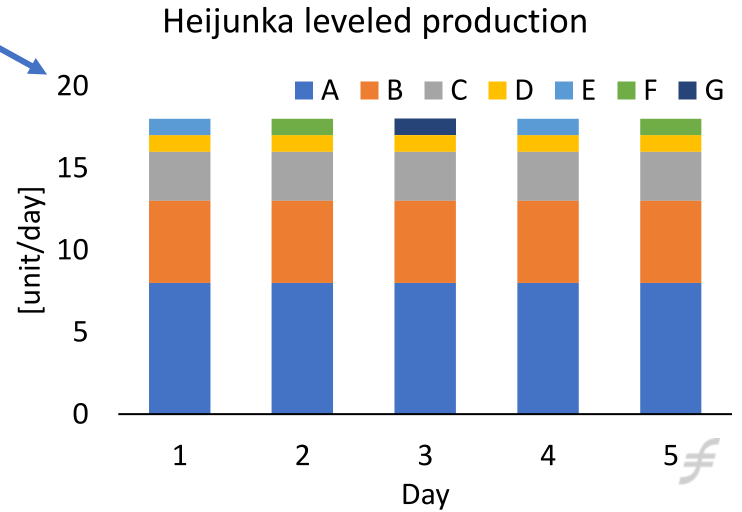

Source: McKinsey Ops Training Material

# Smooth the flow - Heijunka



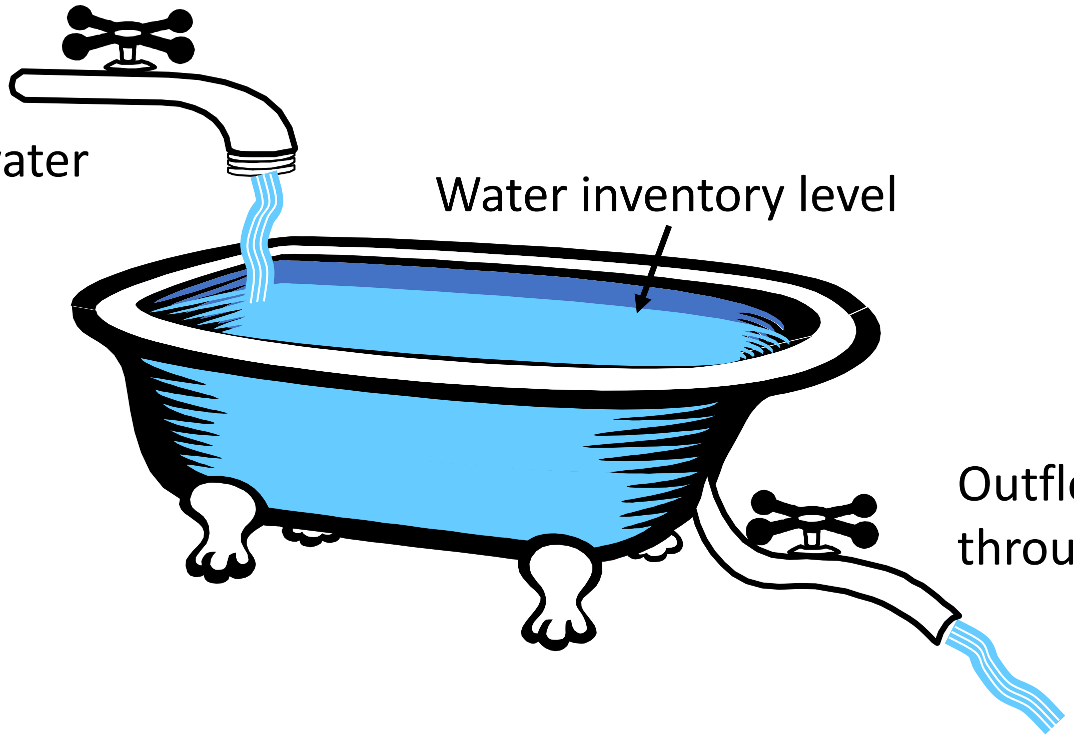

| | Product | | | | | | |
|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G |
| Weekly demand [units/week] | 40 | 25 | 15 | 5 | 2 | 2 | 1 |



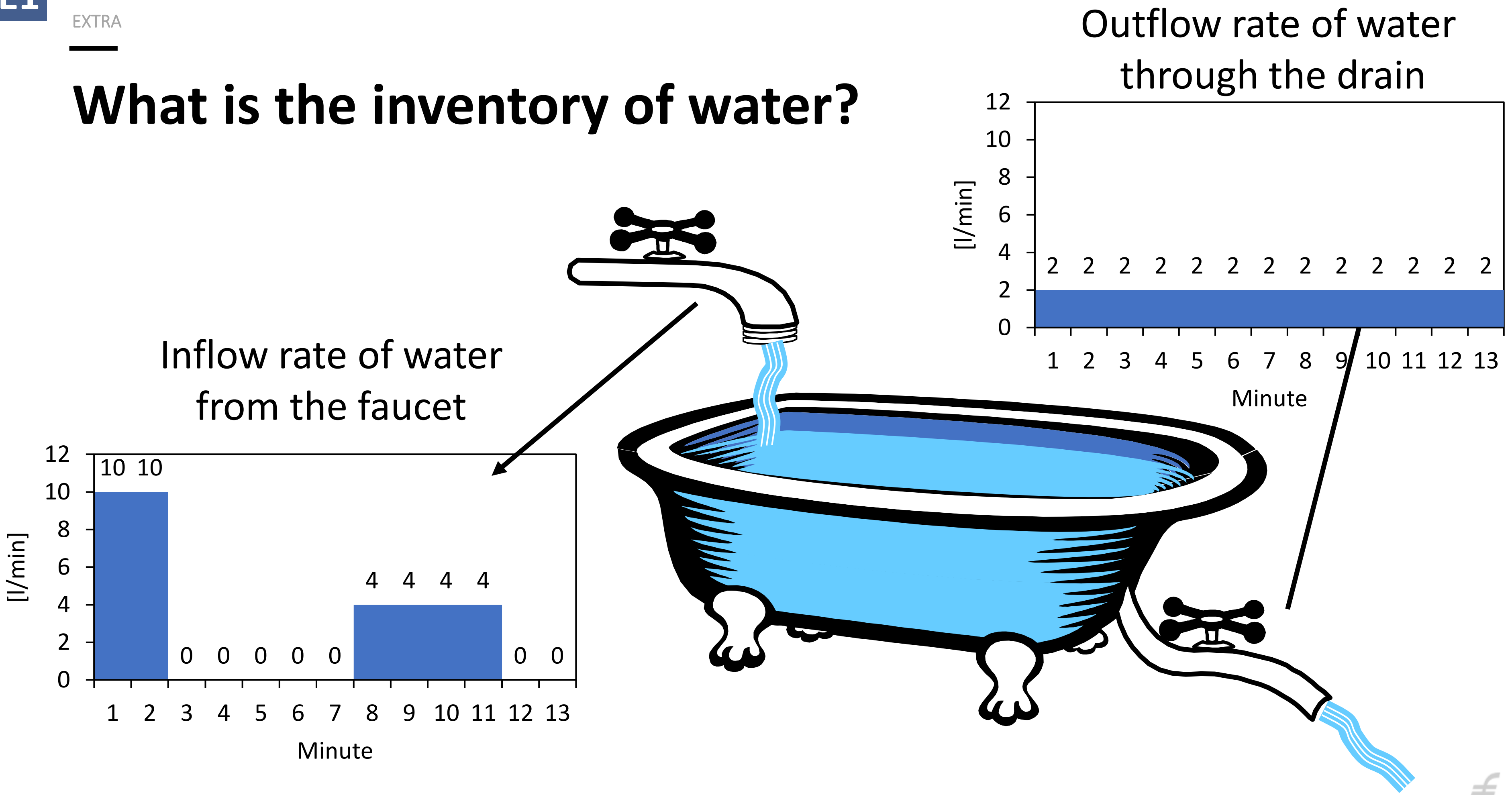



# EXTRA

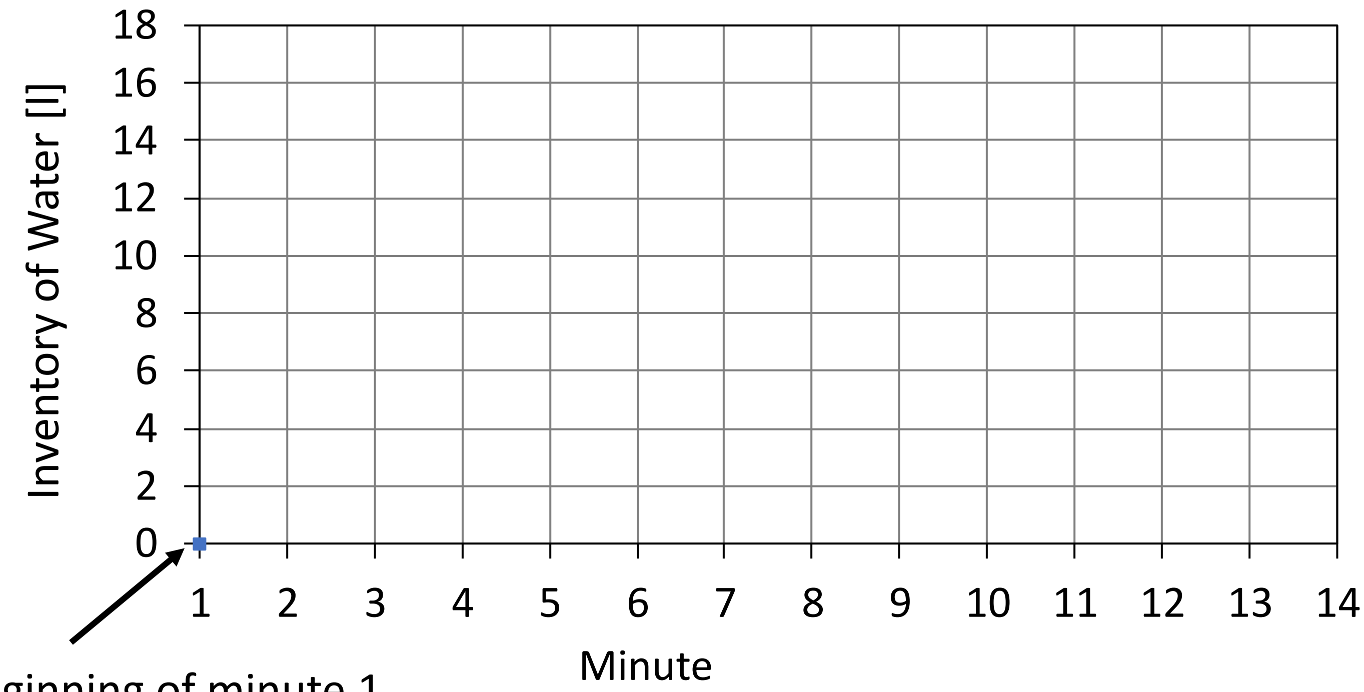
# Inventory of Water in a Bathtub



# What is the inventory of water?



# Inventory of Water




At the beginning of minute 1 the bathtub is empty!

# Three Soups and Dividing Demand



- Suppose one kind of soup is added, but total demand remains the same: 175 l/hour.
- A batch is still a set of vegetable, tomato and potato soup.
- What batch size minimizes inventory?

| | Vegetable | Tomato |
|---|---|---|
| Demand [l/h] | 80 | 65 |
| Setup time [h] | 0.4 | 0.4 |
| Production rate [l/h] | 300 | 300 |

| | Potato |
|---|---|
| Demand [l/h] | 30 |
| Setup time [h] | 0.4 |
| Production rate [l/h] | 300 |

# Three Soups Dividing Demand Analysis

- Desired capacity (or flow rate) is 80 + 65 + 30 = 175 l/hour.
- Each batch involves producing vegetable, tomato and potato soup, so the total setup time is 0.4 h + 0.4 h + 0.4 h = 1.2 hours per batch.
- Processing time = 1/300 hour per liter.
- Recommended batch size:
- Production:

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1

# LEAN OPERATIONS AND THE TOYOTA PRODUCTION SYSTEM

# Ford vs Toyota Production System

- Taylorism: “The one best way”
- Moving line ensuring working at same pace
- Process driven by huge, rapid machinery with inflexible batch production

1903
1st car

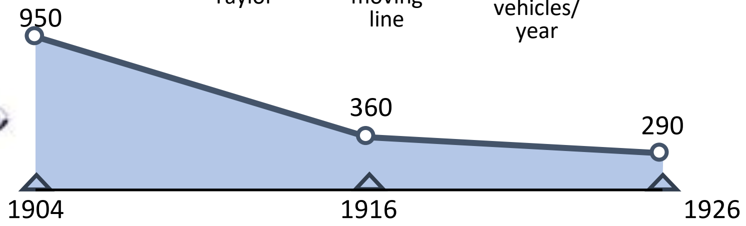
1908
1st Model T

1911
F.W.
Taylor

1913
1st
moving
line

1923
2.1 million
vehicles/
year

Cost
USD/unit




Key idea of Ford: cost reduction through cheap labor, economies of scale, and high utilization
→ cheap car for everyone

Mass production driven by economies of scale impossible
- Low production volume (1950):
  Ford 3,656,000 – Toyota 11,000
- Low productivity (Japan 1/9 of US)
- Lack of resources

1933
Founded

1946
Major strike

1950
Start of
TPS

1960s
Supplier
develop-
ment

1980s
Trans-
plants

Key idea of TPS: systematic elimination of non-value-adding activities

Source: McKinsey

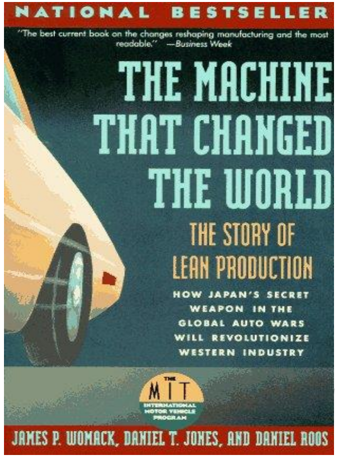
# Some Facts and Figures

| | Assembly Plants, 1986 | |
|---|---|---|
| | Ford Framingham | Toyota Takaoka |
| Gross Assembly Hours per Car[a] | 40.7 | 18 |
| Assembly Defects per 100 Cars[b] | 130 | 45 |
| Assembly Space per Car [c] | 8.1 | 4.8 |
| Inventories of Parts (average) | 2 weeks | 2 hours |

a) Gross assembly hours per car are calculated by dividing total hours of effort in the plant by the total number of cars produced

b) Defects per car were estimated from the J.D. Power Initial Quality Survey for 1987 (www.jdpower.com)

c) Assembly Space per Car is square feet (0,093 m²) per vehicle per year, corrected for vehicle size



# Lean Operations

Lean = Elimination of waste

Two categories of waste

- Waste of time of a resource
- Waste of time of a flow unit

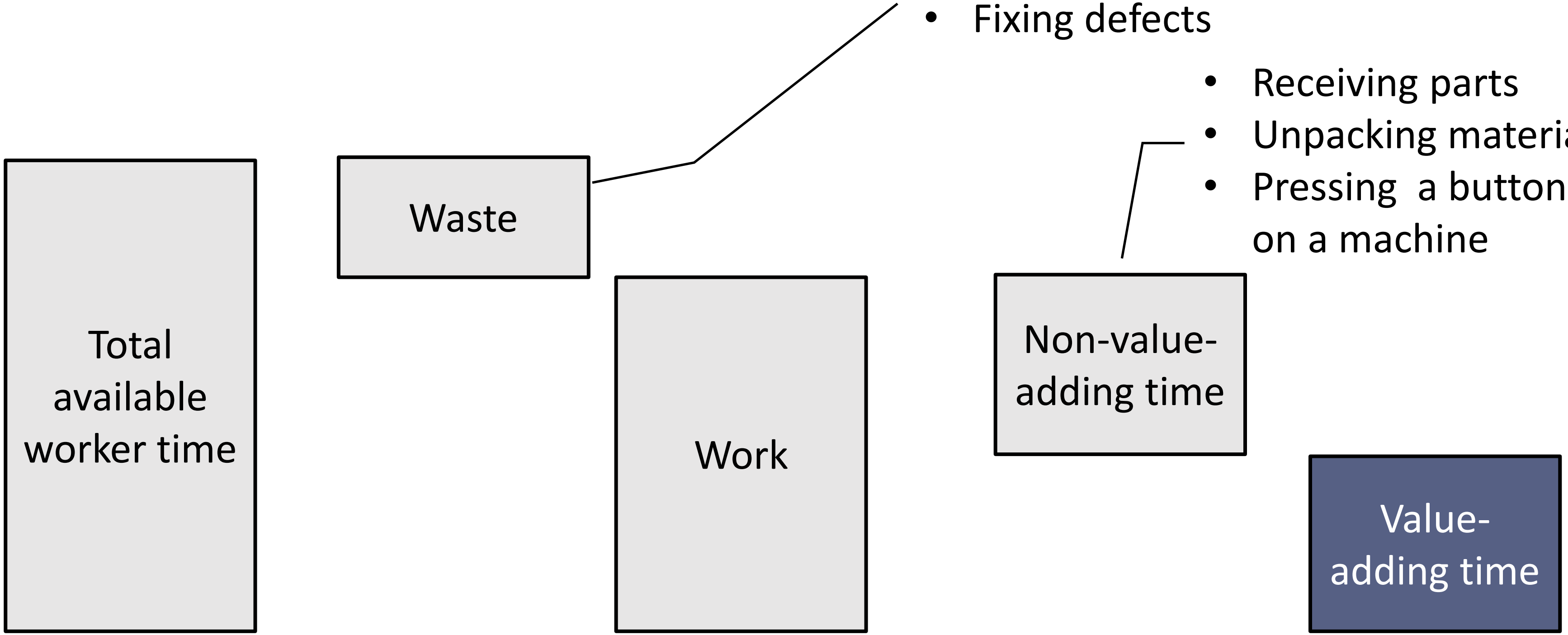
# Seven Sources of Production Waste to be Eliminated

1. Waiting time (of resources and flow units)
2. Overproduction (too much too soon)
3. Excess inventory (result of overproduction, inadequate inventory models)
4. Unnecessary transporting (inadequate physical layout)
5. Overprocessing (spending more time on a flow unit than necessary, processing waste)
6. Rework (takes away time that could be used in regular production)
7. Unnecessary motions and movement (Taylor: There are many ways to perform a task, but there is only one right way.)

# Waste of Time at a Resource

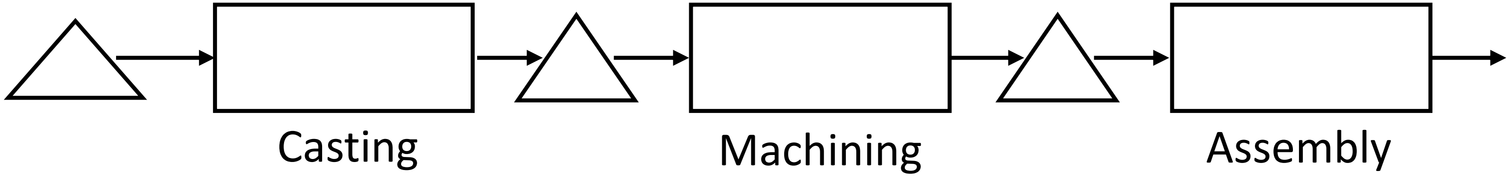
- Idle time
- Meaningless transport
- Stockpiling of inventory
- Fixing defects

- Receiving parts
- Unpacking materials
- Pressing a button on a machine

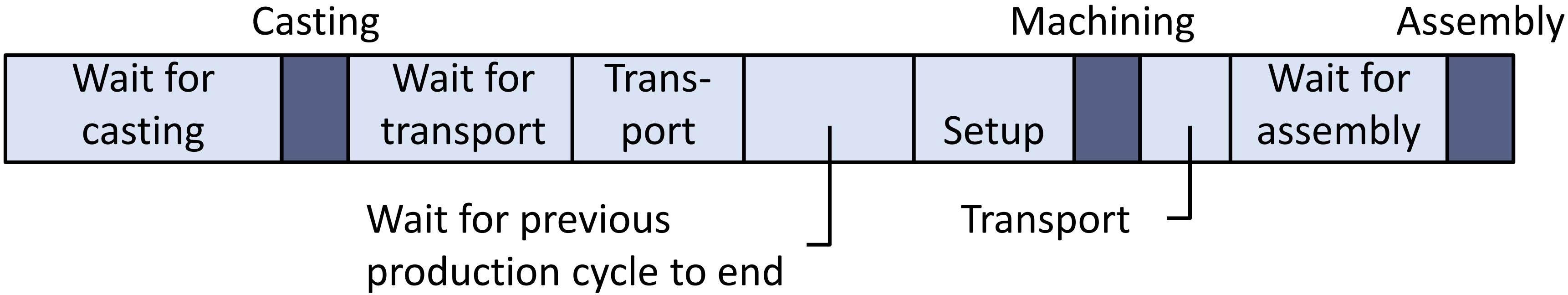



$$\text{Overall Equipment Effectiveness OEE} = \frac{\text{Value–adding time}}{\text{Total available time}}$$

# Waste of Time of a Flow Unit




Perspective of one flow unit:




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

This topic
Other topics

# The Toyota Production System House

Matching
Supply with Demand

Better flow (no wasted time)

Better use of resources (no wasted capacity)

**Just-in-Time Flow**
Produce in the amounts needed, when needed, and where needed using a single-unit-flow

| | |
|---|---|
| Piece-by-piece transfer (ikko-nagashi) | Fast changeovers |
| U-shaped lines/cells | Mixed-model production (heijunka) |
| Pull production (Kanban) | Takt time |

**Built-in Quality**
Detect and address defects when and where they occur and prevent them from recurring

| | |
|---|---|
| Detect-stop-alert(jidoka) | Six sigma |
| Inspection policy | Process capability |
| Stop the line (andon) | Control charts |

Process Improvement: Problem solving and process improvement are led by the workers (kaizen)

| | | | | |
|---|---|---|---|---|
| Go and see yourself (genchi genbutso) | Root cause | Control charts | Pareto analysis | Foolproofing |

Stable Processes: Create a stable and smooth flow with little variability and built-in flexibility

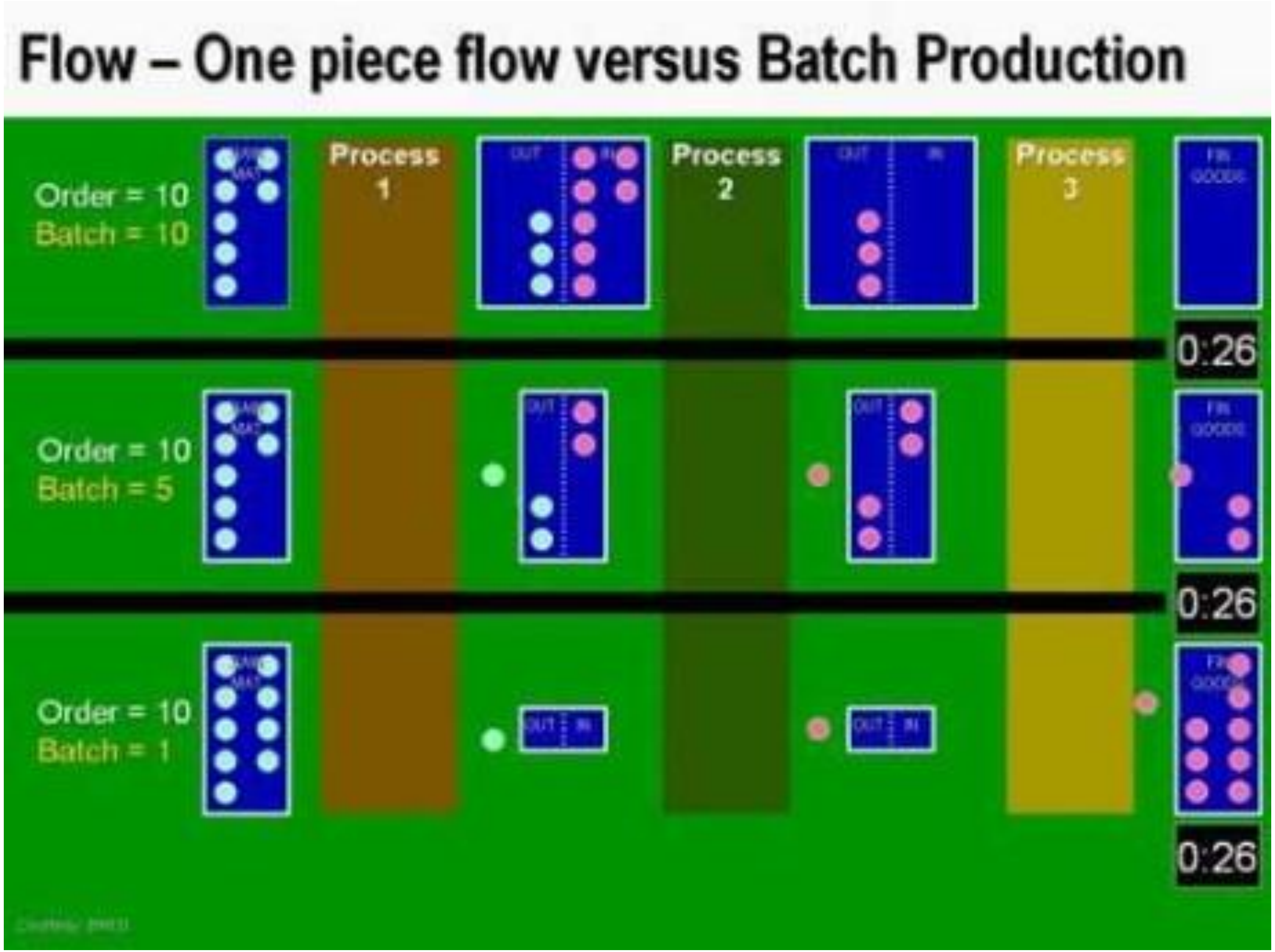
| | | |
|---|---|---|
| Level production | Built-in flexibility | Variability and flow |

# Just-in-time Flow

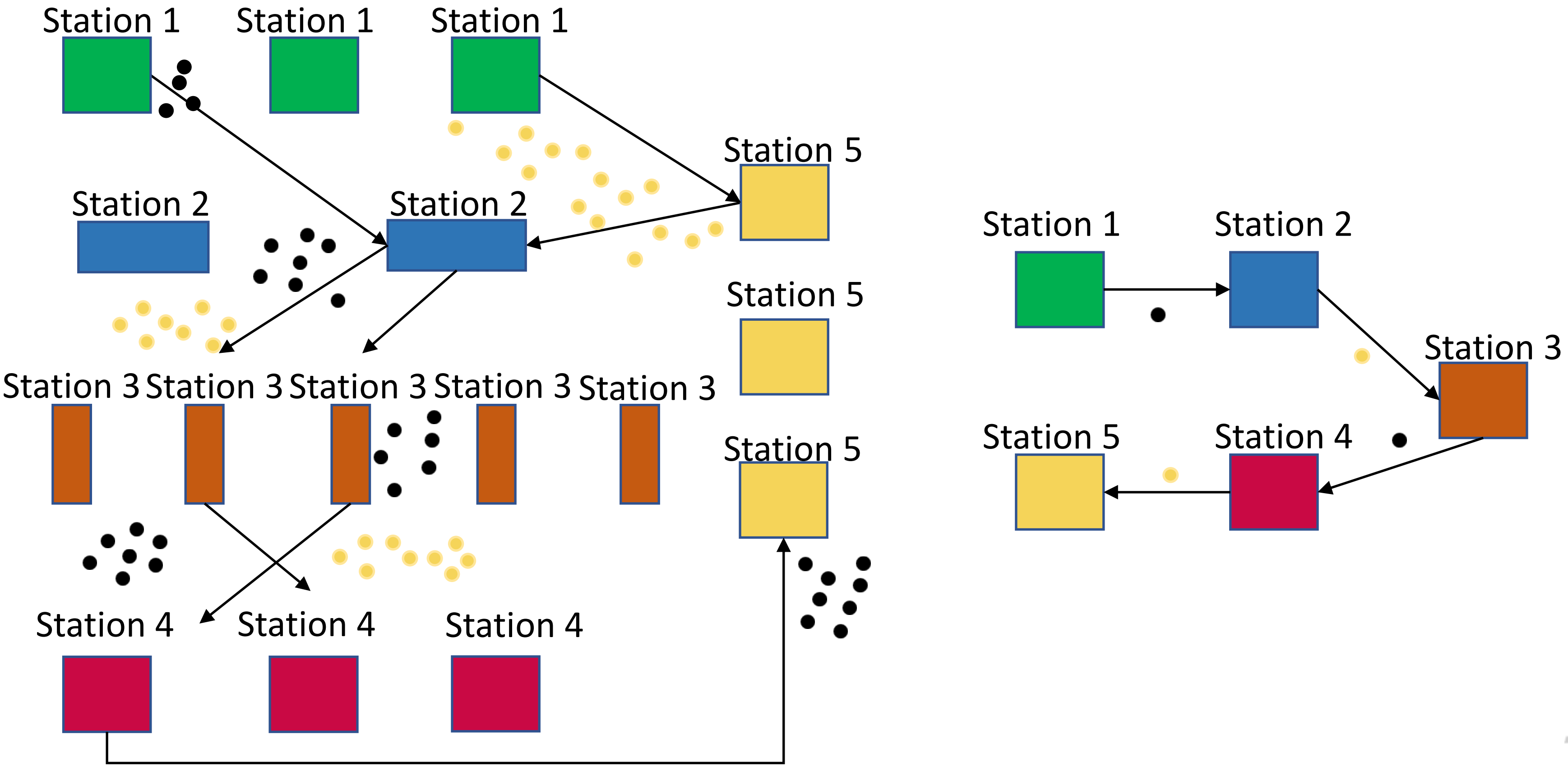
Just-in-time goal

- Create a supply process that forms a smooth flow with its demand, thereby giving customers exactly what they need, when they need it
- Run like the tortoise, not the hare


THE TORTOISE AND THE HARE

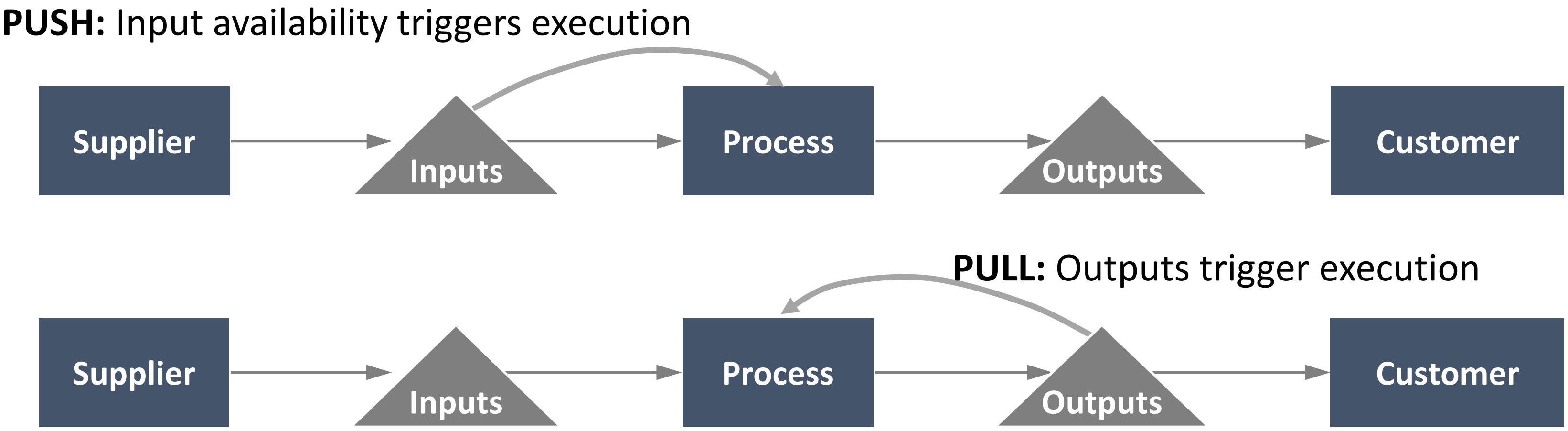

Flow – One piece flow versus Batch Production
Order = 10
Batch = 10
Process
1
Process
2
Process
3
0:26
Order = 10
Batch = 5
0:26
Order = 10
Batch = 1
0:26

# U-shaped Work Cell with Piece-by-piece Transfer



# Push versus Pull

- Push: Flow units are allowed to enter the system independent of current amount of inventory in the system and independent of customer demand

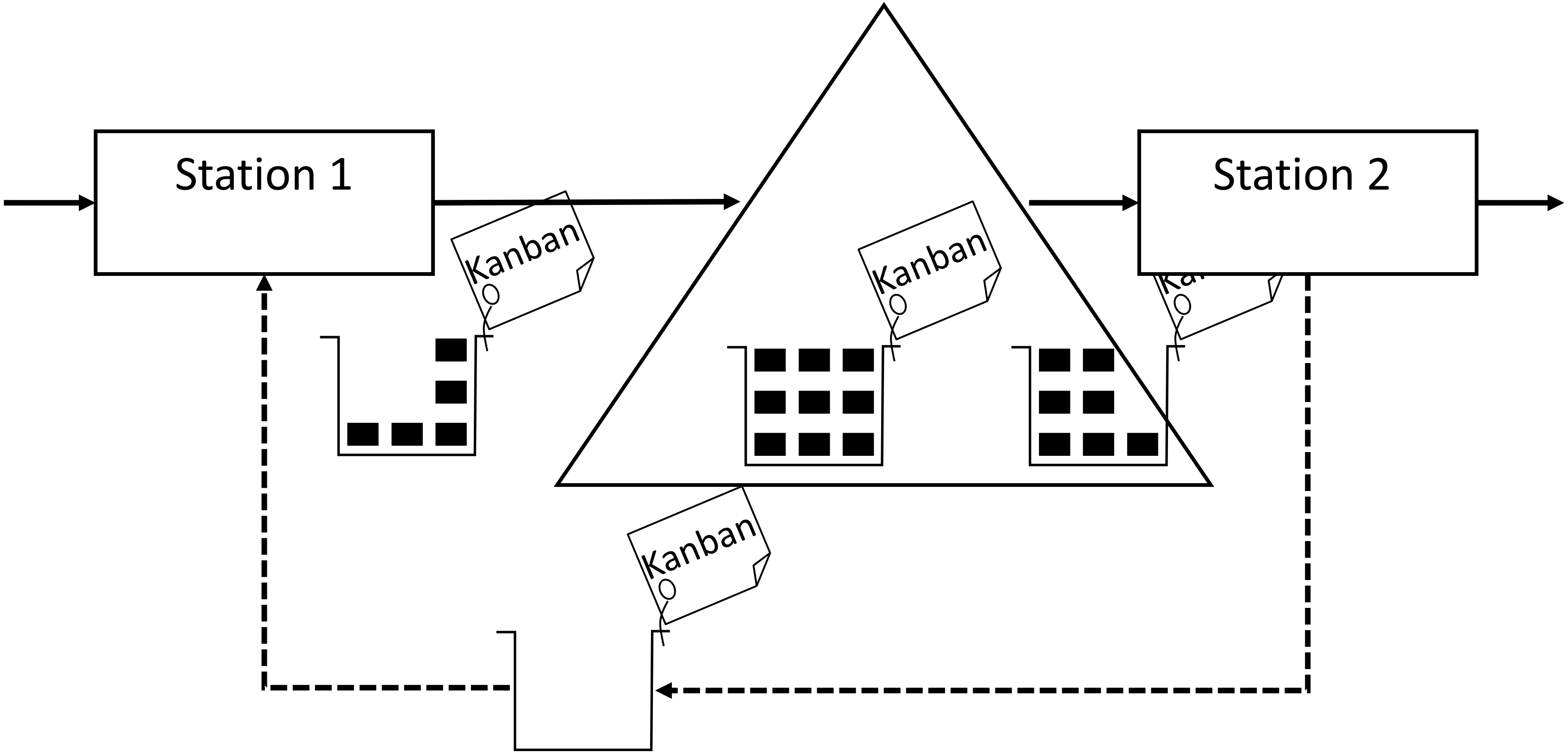



- Pull: the resource furthest downstream (i.e., closest to the market) triggers production

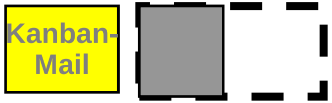
# Implementation of a Pull System: Kanban

- Kanban-based pull (also known as supermarket)
- Returnable parts containers circulate between upstream and downstream resources
- The upstream resource is allowed to produce only, when it received an empty container → the arrival of an empty container triggers production
- Kanban refers to the card attached to the container which includes “production orders“
- Main advantage: there can never be more inventory in the system than has been authorized by Kanban cards; production stops if all containers are full

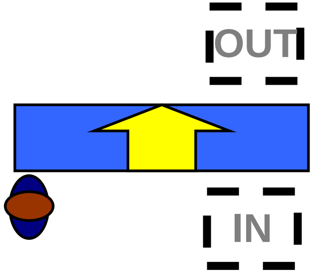
# Kanban control overview



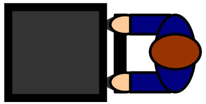
# Explanation of Symbols Used in Kanban Animation



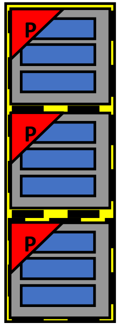

Kanban-Mail and KLT-bin



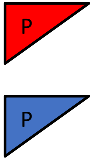

Machine with operator, input and output area



Logistics-staff



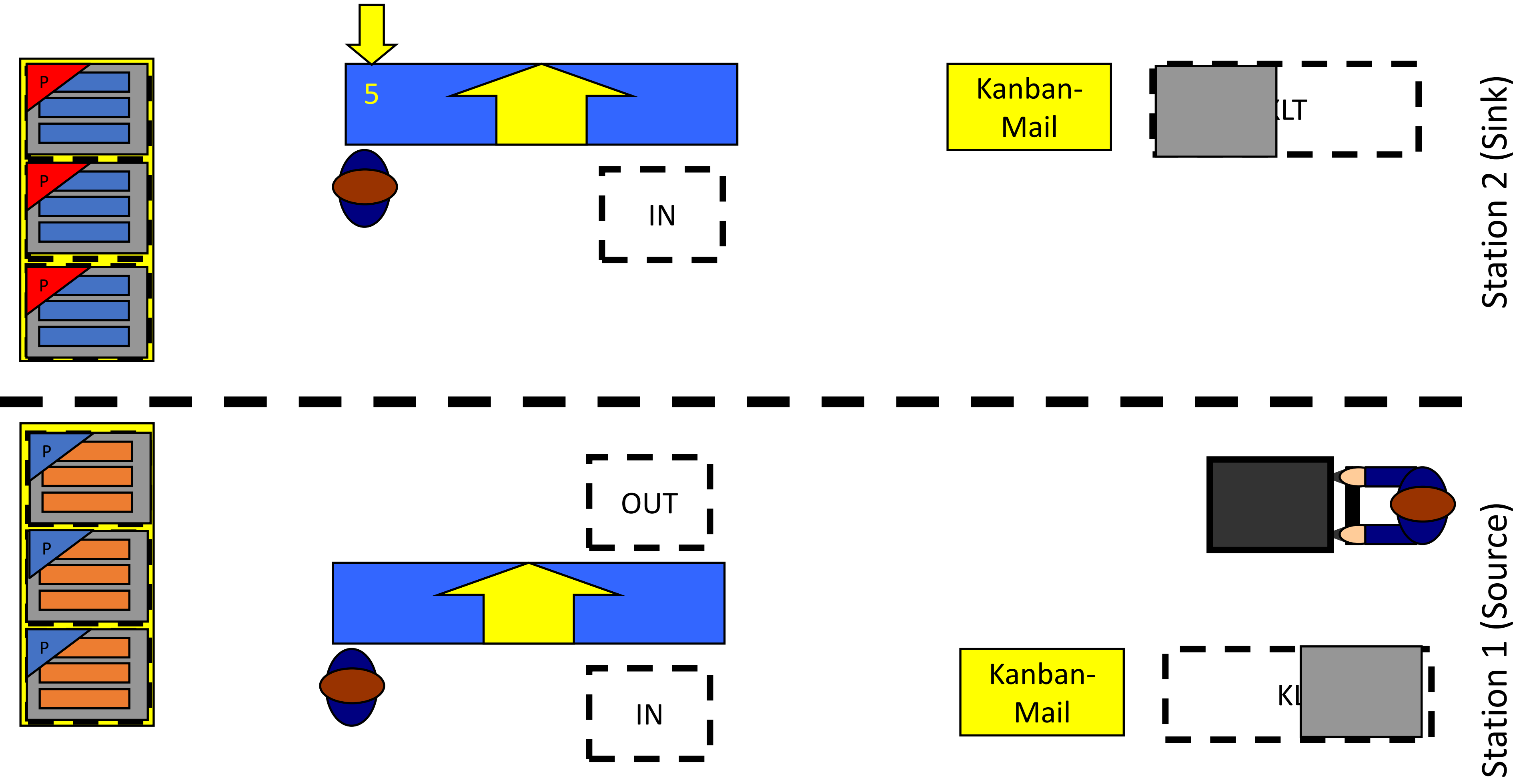
Kanban-buffer with Kanbans ( ) and small load KLT* box ( ) filled with componentss ( ).

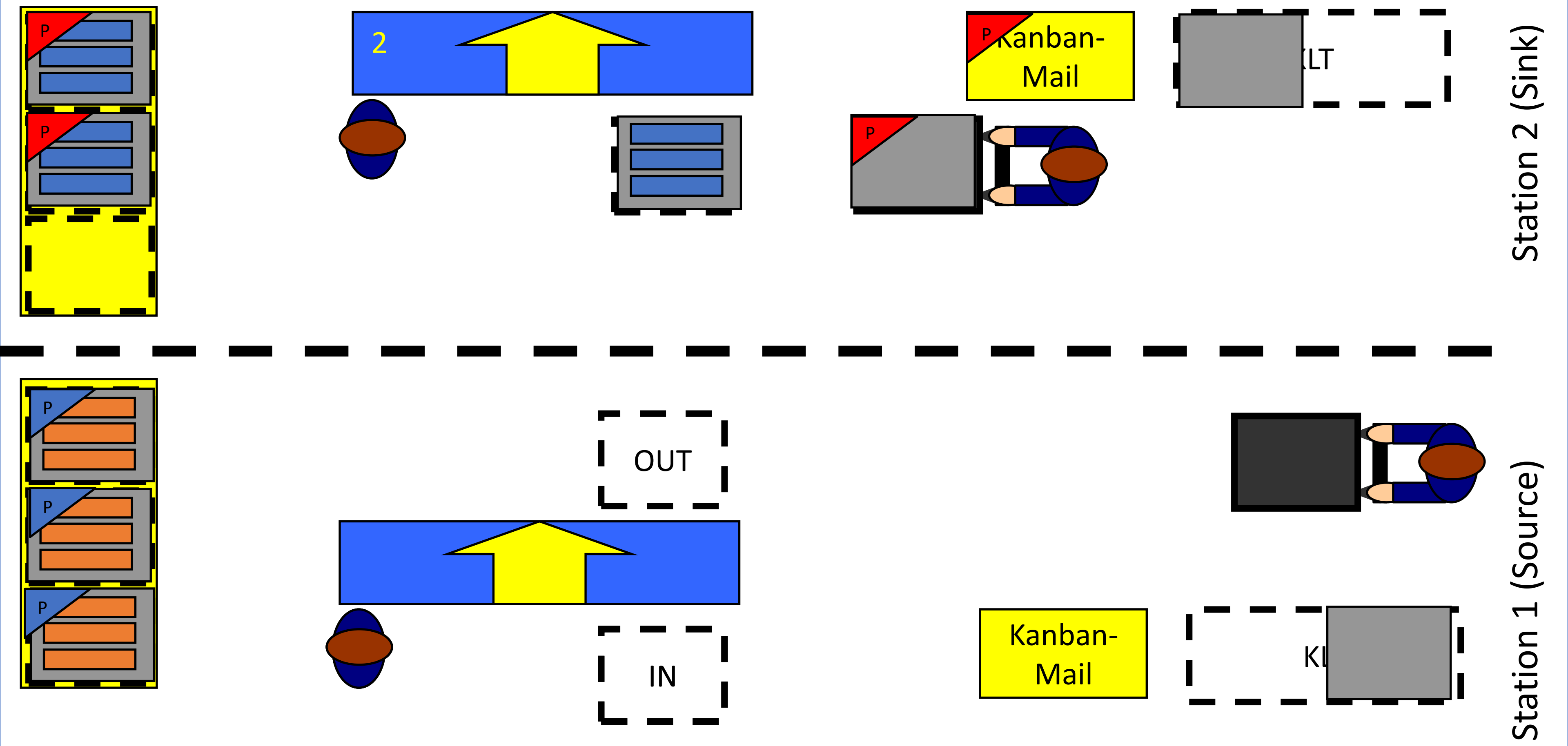


Kanban- Lot size = 3 Components

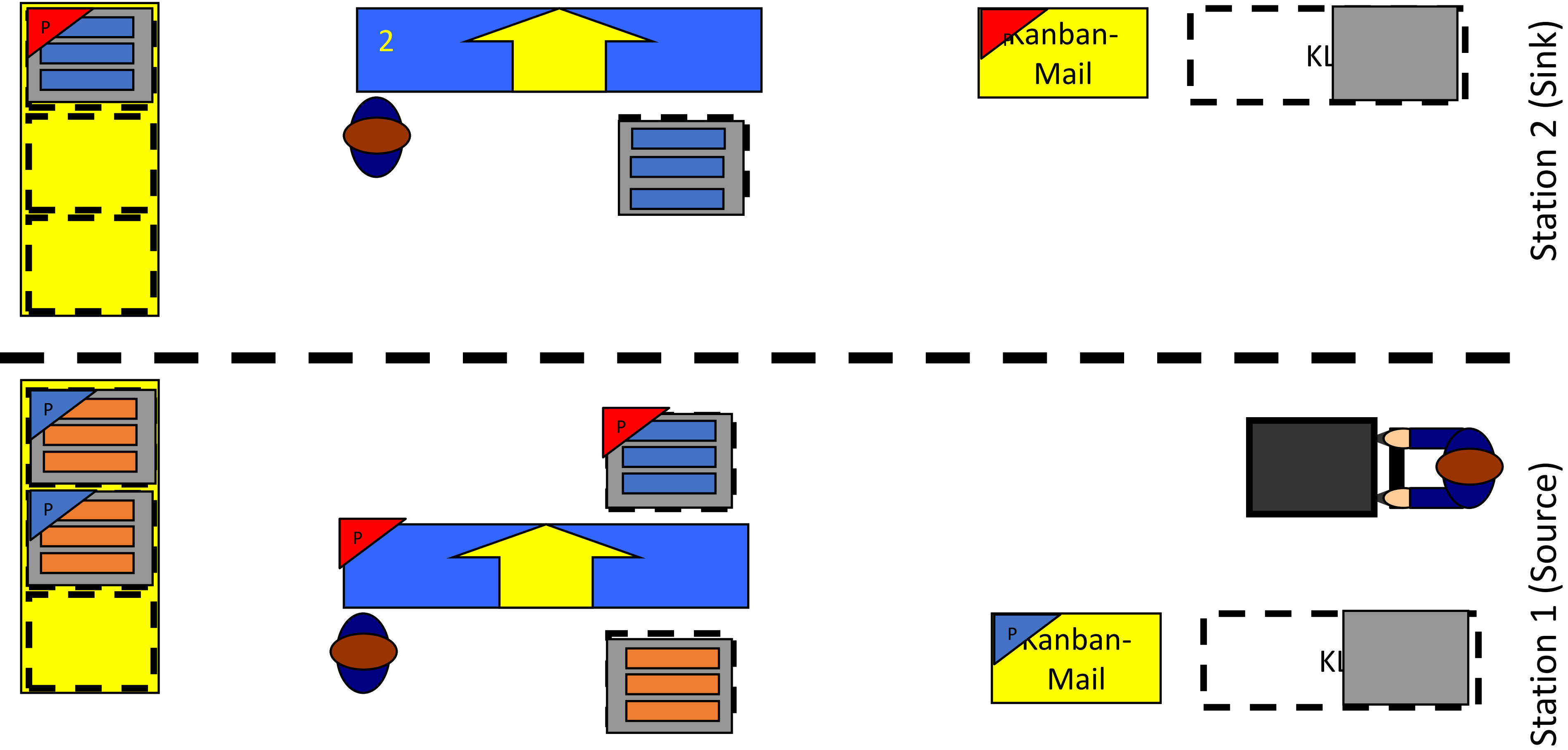
* KLT = Kleinladungsträger, Eurocontainer

Mit besonderem Dank an Prof. Dr. Thun


5
Kanban-
Mail
KLT
IN
Station 2 (Sink)
OUT
IN
Kanban-
Mail
KL
Station 1 (Source)
P



P
P
2
P
Kanban-
Mail
KLT
P
Station 2 (Sink)
P
P
P
OUT
IN
Kanban-
Mail
KL
Station 1 (Source)

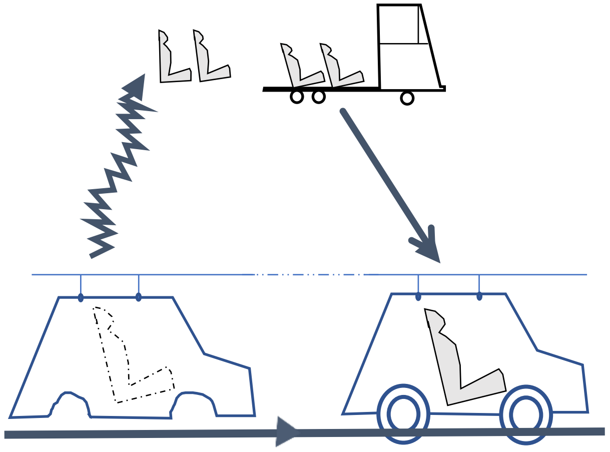


P
2
Kanban-Mail
KL
Station 2 (Sink)
P
P
P
P
P
Kanban-Mail
KL
Station 1 (Source)

# Implementation of a Pull System: Make-to-Order Process

- A Pull system can also be implemented by Make-To-Order processes
- Part produced for specific order (at supplier)
- Shipped right to assembly → Real time synchronization
- Make-to-Order: In a pure make-to-order setting production is purely triggered by the end-customer
- Common for low-volume products with high customization; customers must be willing to wait; no finished products inv.

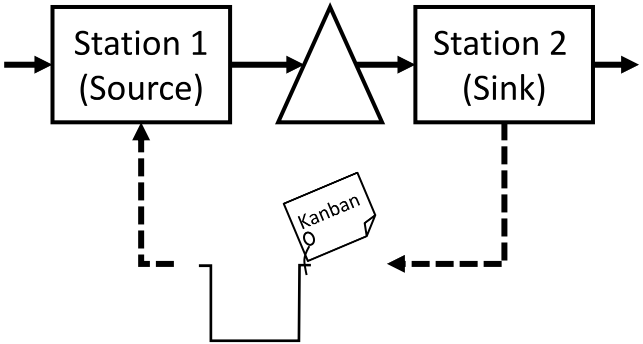
**Pull: Synchronized production**



# When to use Kanban, When to use Make-to-Order?

Pull: Make-to-order production

Pull: Kanban




Make-to-Order should be used when:
- products are processed in low volume and high variety.
- customers are willing to wait for orders.
- it is expensive or difficult to store products.

Kanban should be used for products that:
- are processed in high volumes and limited varieties.
- are required with a short lead time → it is reasonable to preproduce (#Kanban cards).
- have low storing costs and efforts.

This topic
Other topics

# The Toyota Production System House

Matching
Supply with Demand

Better flow (no wasted time)
Better use of resources (no wasted capacity)

| Just-in-Time Flow<br>Produce in the amounts needed, when needed, and where needed using a single-unit-flow | | Built-in Quality<br>Defect and address defects when and where they occur and prevent them from recurring | |
|---|---|---|---|
| Piece-by-piece transfer (ikko-nagashi) | Fast changeovers | Detect-stop-alert(jidoka) | Six sigma |
| U-shaped lines/cells | Mixed-model production (heijunka) | Inspection policy | Process capability |
| Pull production (Kanban) | Takt time | Stop the line (andon) | Control charts |

Process Improvement: Problem solving and process improvement are led by the workers (kaizen)

| Go and see yourself (genchi genbutso) | Root cause | Control charts | Pareto analysis | Foolproofing |
|---|---|---|---|---|

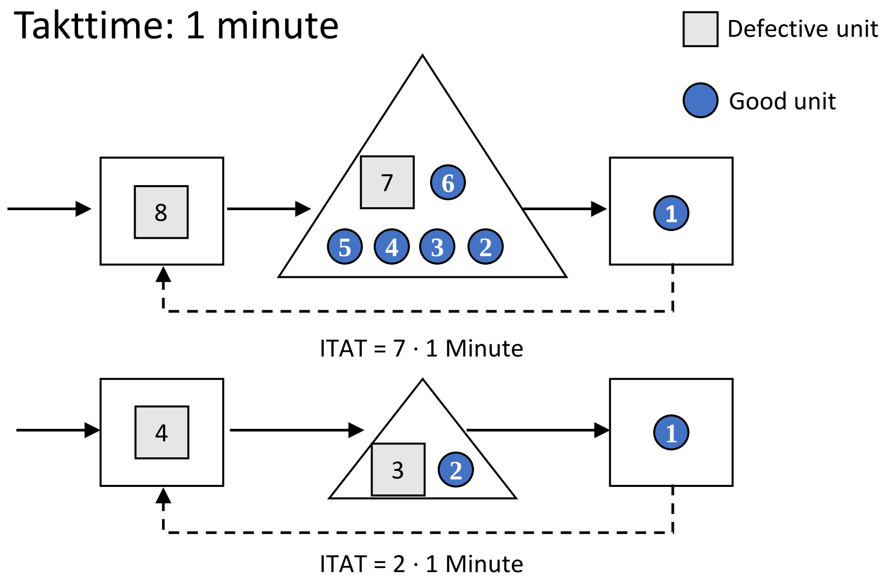
Stable Processes: Create a stable and smooth flow with little variability and built-in flexibility

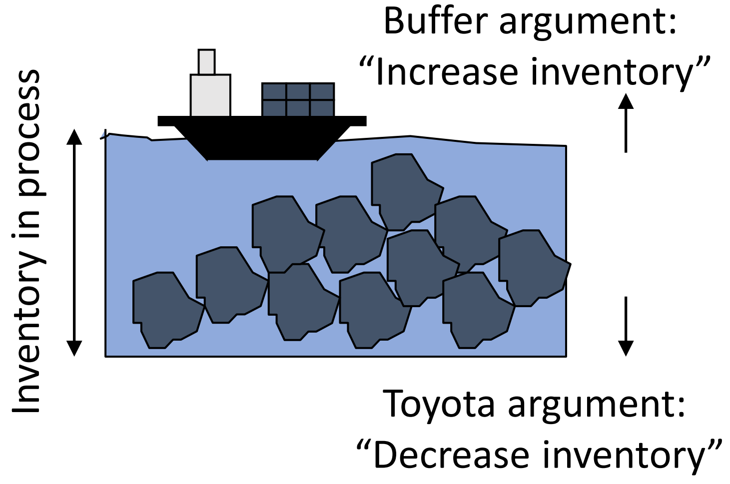
| Level production | Built-in flexibility | Variability and flow |
|---|---|---|

# Detect-Stop-Alert (Jidoka)

- To approach “zero defects“, TPS relies on
  - Defect prevention
  - Rapid defect detection
  - Strong worker responsibility
- Jidoka
  - If, despite defect prevention, a defect occurs, TPS attempts to detect this defect ASAP
  - Stop the machine/assembly immediately if a defect is detected: Andon cord
  - Inspection policy: In contrast to GM/Ford where quality inspection comes at the end of the process every worker proofs quality such that quality inspection is “built in“ the process (tsukurikomi).
- Large WIP inventories delay the detection of quality issues (opposite of Jidoka)

# Inventory Delays the Detection of Errors




- Inventory leads to a longer ITAT (Information turnaround time) ⇨ slow feed-back and no learning
- TPS philosophy: expose problems instead of hiding them
- However, zero inventory may become a problem! … (right figure)

This topic
Other topics

# The Toyota Production System House

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Supply with Demand

Better flow (no wasted time)

Better use of resources (no wasted capacity)

**Just-in-Time Flow**
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| | | |
|---|---|---|
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# Kaizen

- Continuous improvement
  - Build an organizational culture and value system that stresses improvement of all processes
  - Part of everyone’s job
- Respect for people
  - People are treated as knowledge workers
  - Engage physical and mental capabilities
  - Empower employees

# Genchi Genbutsu

- The Ohno Circle: Stand in the circle and observe
- Gary Convis: President moves to shop floor
- Sienna Chief Engineer: ”I must drive through all 50 states and all Canadian provinces and territories and Mexico”
- Engineering: Go and see where the actual parts are made and tested

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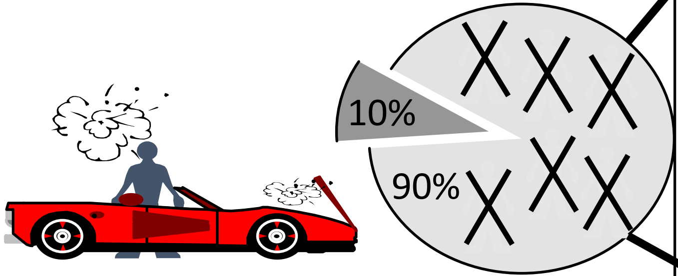
# 2023
# Operations Management

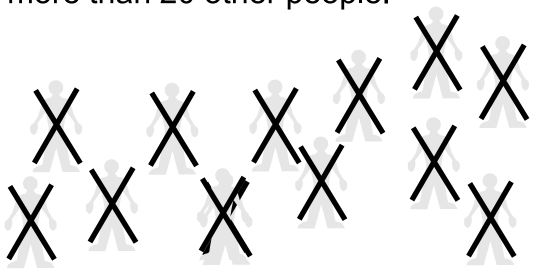
# QUALITY AND STATISTICAL PROCESS CONTROL

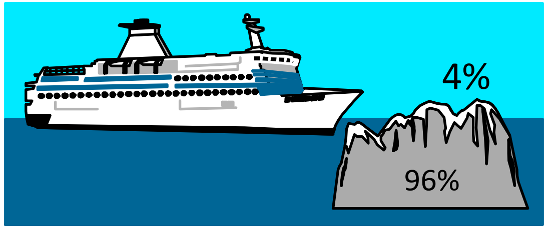
# Effect of Quality Issues- Customers

“90% of the customers being unsatisfied with a product won‘t use it in the future.”



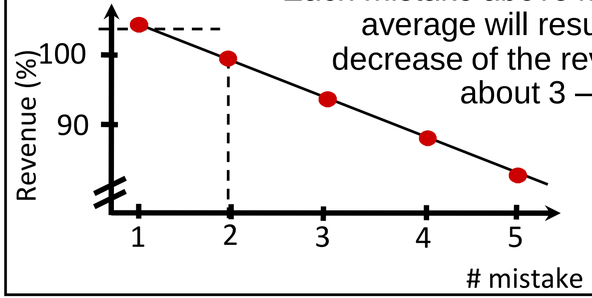

Each of these customers will tell his negative experience at least 9 or even more than 20 other people.”





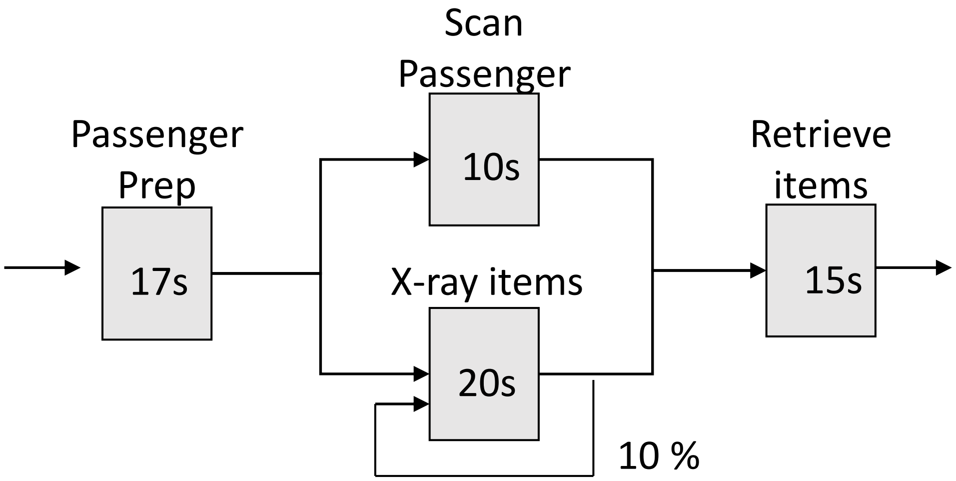

“Only 4% of the unsatisfied customer will complain about bad quality.”

“Each mistake above market average will result in a decrease of the revenue about 3 – 4 %.“




Quelle: Robert L. Desatnik: Long Live the King, in: Quality Progress, April 1989.

# Effect of Quality Issues – Rework



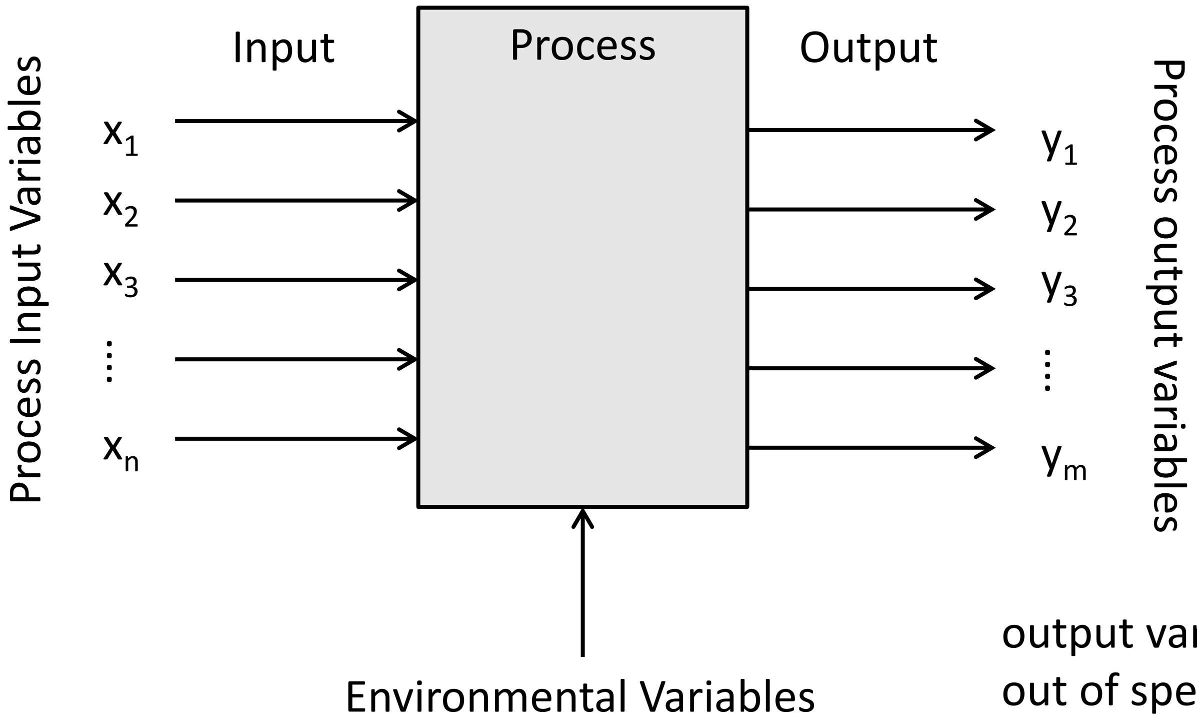

- Process flow diagram: Airport security check
- Bottleneck: X-ray items
- Capacity without quality issues/rework: 3 [passengers/min]
- Suppose: 10% of passenger baggage need to be rescanned
  - Avg. processing time of X-ray items = $0.9 \cdot 20$ [s] + $0.1 \cdot 40$ [s] = 22 [s]
  - Capacity decreases to 1/22 [passengers/s] · 60 [s]/[min] = 2.73 [passengers/min]

  → The system‘s capacity is reduced by 9 % due to re-work!

# Variation

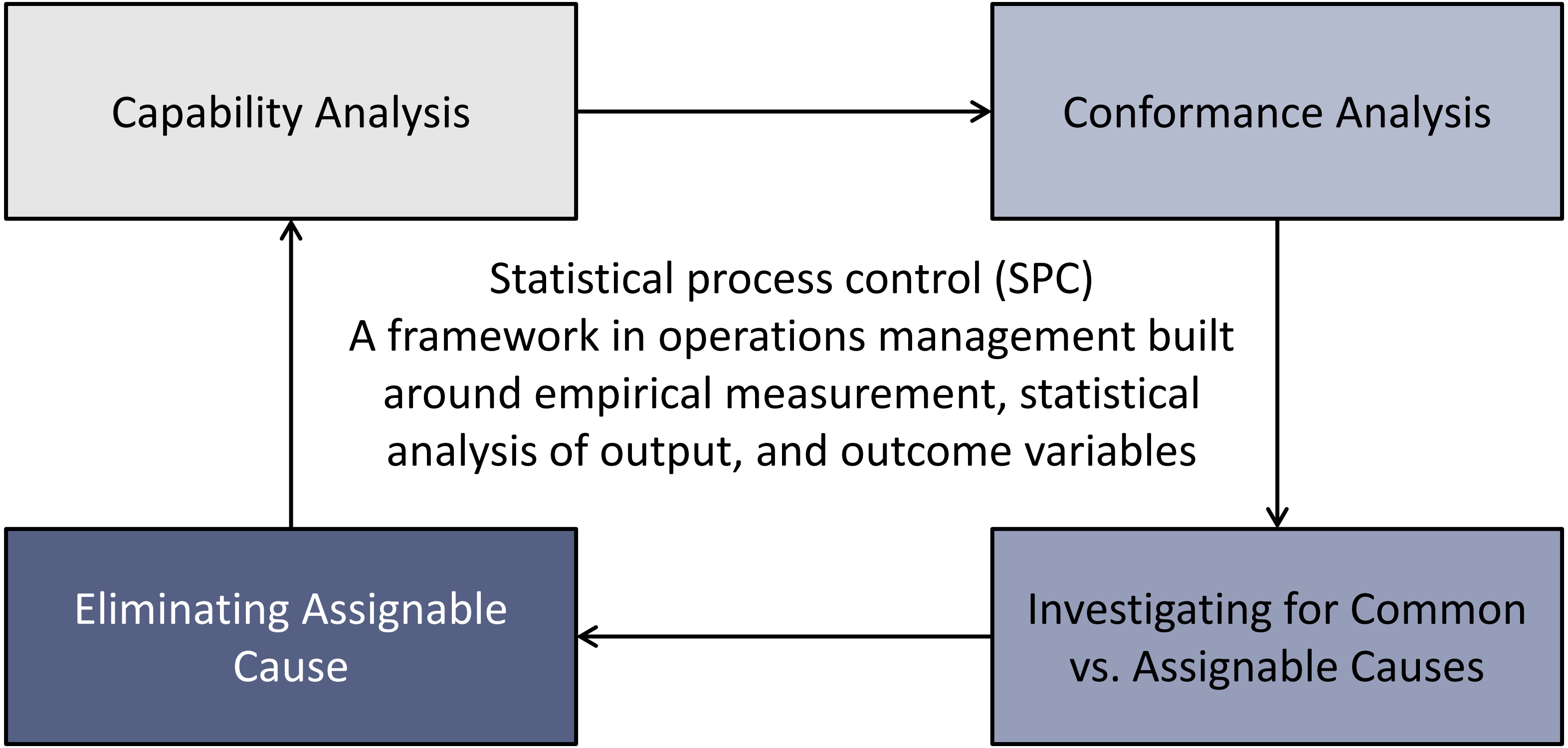
- Variation exists everywhere.
- Defects are driven by variability.

# Variation in a Process



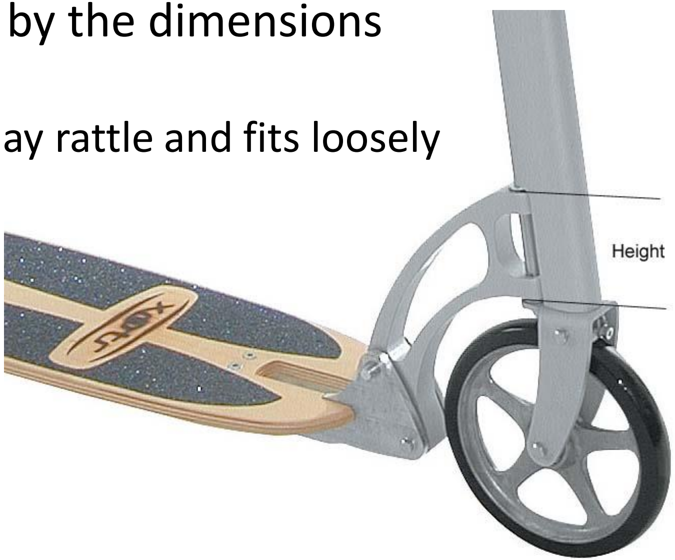

output variable
out of specification
→ defect

# The Statistical Process Control Framework



# Capability Analysis: The Xootr Example

- Steer support part - a critical component of the Xootr scooter
- The "height" of the steer support must closely match the opening in the lower handle
- The "height" of the steer support is specified by the dimensions as falling between 79.900 and 80.000 mm
  - If the height is less than 79.900 mm the part may rattle and fits loosely → lower specification limit (LSL)
  - If the height is more than 80.000 mm it does not fit in the gap → upper specification limit (USL)
- Specification limits determine which units are acceptable/defective



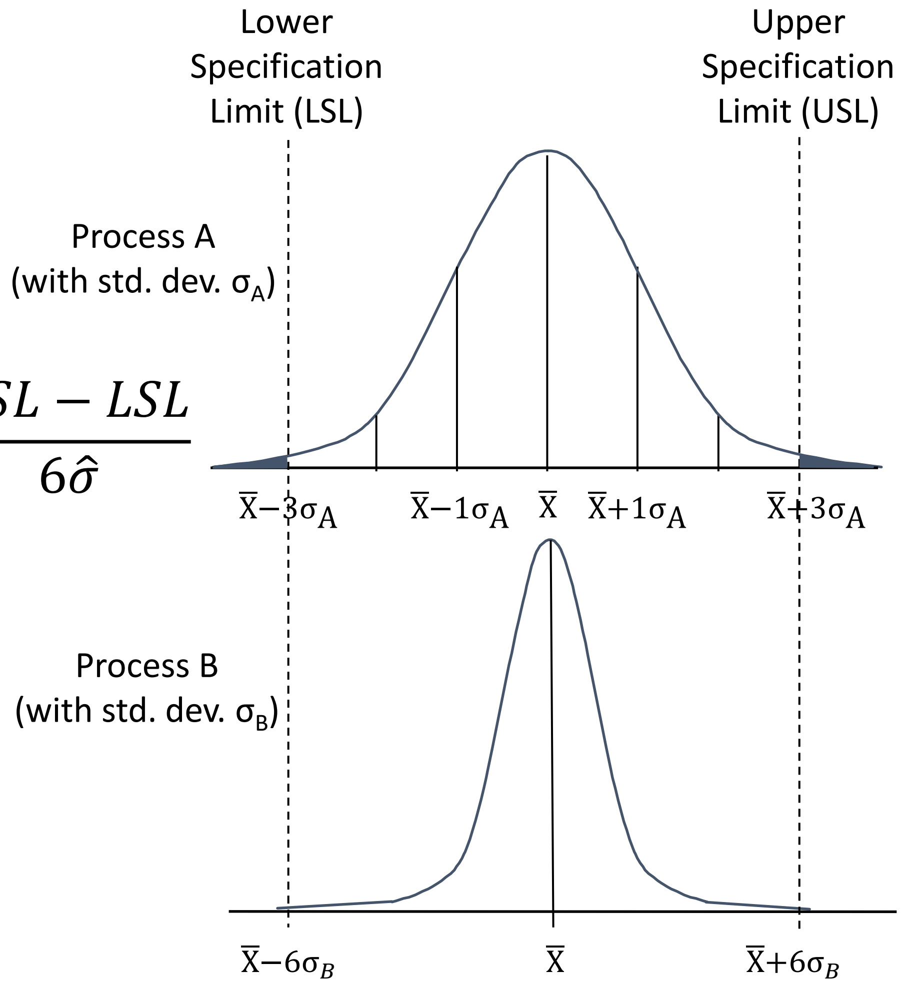
# Sources of Variation in the CNC Milling Process

- The steer support is refined by a high-precision CNC machine
- Nevertheless, there is variation in the output, resulting from
  - CNC machine characteristics, e.g. positioning error,
  - Changing raw material quality,
  - Changes in temperature,
  - CNC operator mistakes, etc.

# Determining the Process Capability Index

- The process capability measure, $C_p$, relates the process tolerance to the actual variation captured by the estimated standard deviation.
- Process tolerance in relation to actual variation
- $C_p=1$: probability of 99.7% that specifications are met ⇨ "3-Sigma"
- $C_p=0.6$: probability of 92.8% , that specifications are met
- $C_p=2.0$: probability of 99.9999998%, that specifications are met ⇨„6-Sigma"

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



E1

# Process Capability & Defect Probability

LSL: 79.900 mm
USL: 80.000 mm
Xootr engineers estimate a standard deviation of 0.017291 mm.

- Probability {part too small}
  = NORM.DIST(79.900, 79.950, 0.017291, TRUE) = 0.001915954
- Probability {part too big}
  = 1-NORM.DIST(80.000, 79.950, 0.017291, TRUE) = 0.001915954
- Probability {part defective}
  = 0.001915954 + 0.001915954
  = 0.003831908
- Defective parts per million (PPM)
  = 0.003831908 · 1,000,000 = 3831.9

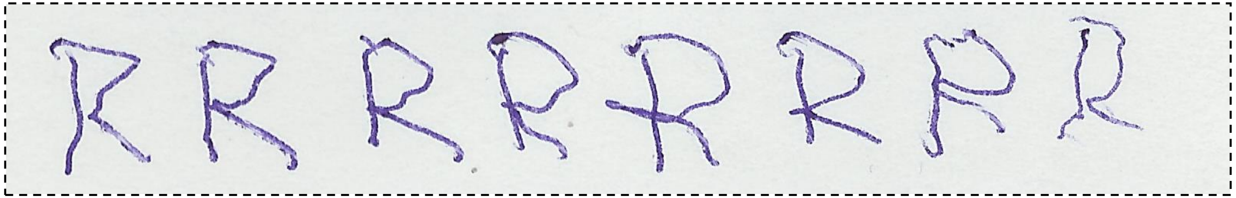
$$C_p = \frac{USL - LSL}{6\hat{\sigma}} = \frac{80.000 - 79.900}{6 \cdot 0.017291} = 0.96389$$

# Conformance Analysis - Two Types of Variation

- Common-cause variations („natural“ variation)
  - No two pieces are exactly identical, but the variation is “within the tolerance“
  - Natural, purely stochastic variation; noise within the system
  - Plotting common cause variation looks like a normal distribution
- Special-cause variation, also assignable-cause variation
  - New, unanticipated, emergent or previously neglected phenomena, e.g., error in programming a machine, operator error, material defect, etc.
  - Assignable causes of variation change the underlying statistical distribution of a process
  - Process improvement projects typically address these assignable causes

# Two Types of Variation

Common cause (Low level of Variation)

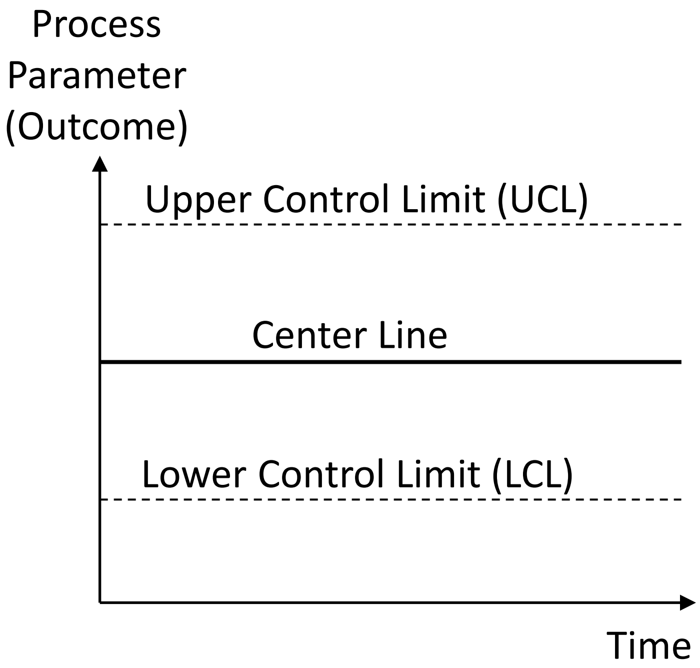


Common cause (High level of Variation)

Assignable Cause Variation

Conformance analysis is about identifying assignable cause variation as soon as possible

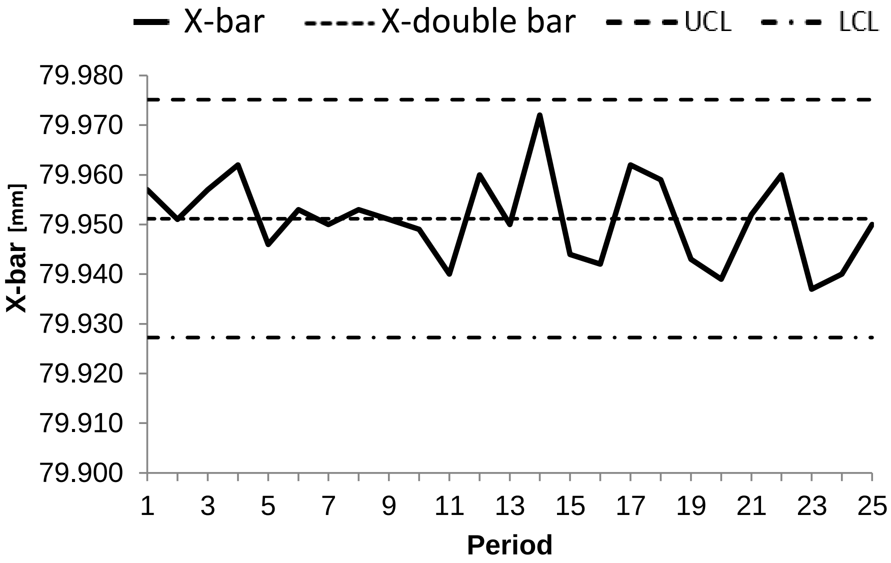
# Detect Abnormal Variation




## Control charts

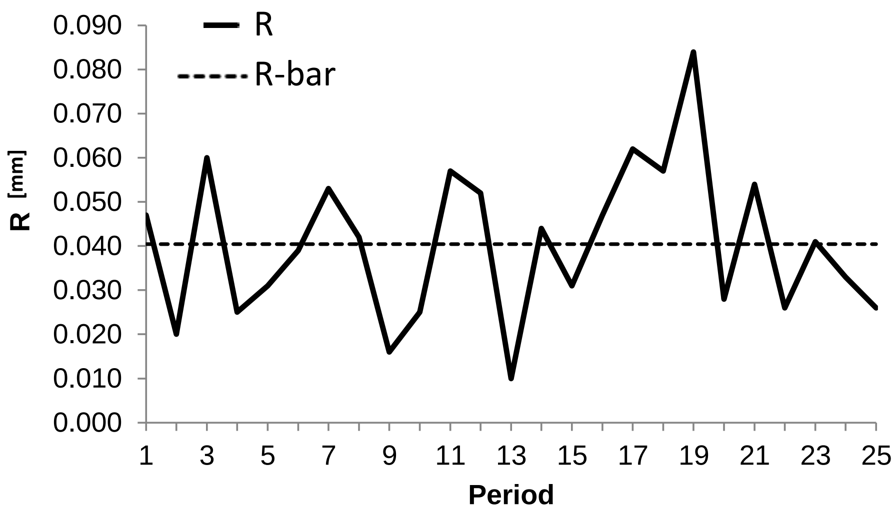
- Graphical tools to statistically distinguish assignable and common cause variation
- Track process outcome over time
  - Mean
  - Standard deviation
- Distinguish between
  - common cause variation (within control limits)
  - assignable cause variation (outside control limits)
- Two types of control charts:
  - X-bar chart
  - R (range)-chart
  - The type of chart (X-bar or R) determines the Y-Axis

# Two Types of Control Charts: X-bar Chart




- Y-axis corresponds to the mean of a sample (e.g., a day)
- Dotted line (X-double bar) is computed from the mean over the sample means
- Used to document trends over time and to identify unexpected jumps (e.g., due to new operator)

# Two Types of Control Charts: R-chart




- Y-axis corresponds to the range of a sample (e.g., a day)
- Range: difference between the highest and the lowest value in a sample OR the standard deviation
- Dotted line is computed from the mean over the sample ranges

# Formulas

| Period | Height of steer support parts in mm | | | | | Mean | |
|---|---|---|---|---|---|---|---|
| | x1 | x2 | x3 | x4 | x5 | (X-bar) | R |
| 1 | 79.941 | 79.961 | 79.987 | 79.940 | 79.956 | 79.957 | 0.047 |
| 2 | 79.953 | 79.942 | 79.962 | 79.956 | 79.944 | 79.951 | 0.020 |
| 3 | 79.926 | 79.986 | 79.958 | 79.964 | 79.950 | 79.957 | 0.060 |
| 4 | 79.960 | 79.970 | 79.945 | 79.967 | 79.967 | 79.962 | 0.025 |
| 5 | 79.947 | 79.933 | 79.932 | 79.963 | 79.954 | 79.946 | 0.031 |
| 6 | 79.950 | 79.955 | 79.967 | 79.928 | 79.963 | 79.953 | 0.039 |
| 7 | 79.971 | 79.960 | 79.941 | 79.962 | 79.918 | 79.950 | 0.053 |
| 8 | 79.970 | 79.952 | 79.946 | 79.928 | 79.970 | 79.953 | 0.042 |
| 9 | 79.960 | 79.957 | 79.944 | 79.945 | 79.948 | 79.951 | 0.016 |
| 10 | 79.936 | 79.945 | 79.961 | 79.958 | 79.947 | 79.949 | 0.025 |
| 11 | 79.911 | 79.954 | 79.968 | 79.947 | 79.918 | 79.940 | 0.057 |
| 12 | 79.950 | 79.955 | 79.992 | 79.964 | 79.940 | 79.960 | 0.052 |
| 13 | 79.952 | 79.945 | 79.955 | 79.945 | 79.952 | 79.950 | 0.010 |
| 14 | 79.973 | 79.986 | 79.942 | 79.978 | 79.979 | 79.972 | 0.044 |
| 15 | 79.931 | 79.962 | 79.935 | 79.953 | 79.937 | 79.944 | 0.031 |
| 16 | 79.966 | 79.943 | 79.919 | 79.958 | 79.923 | 79.942 | 0.047 |
| 17 | 79.960 | 79.941 | 80.003 | 79.951 | 79.956 | 79.962 | 0.062 |
| 18 | 79.954 | 79.958 | 79.992 | 79.935 | 79.953 | 79.959 | 0.057 |
| 19 | 79.910 | 79.950 | 79.947 | 79.915 | 79.994 | 79.943 | 0.084 |
| 20 | 79.948 | 79.946 | 79.943 | 79.935 | 79.920 | 79.939 | 0.028 |
| 21 | 79.917 | 79.949 | 79.957 | 79.971 | 79.968 | 79.952 | 0.054 |
| 22 | 79.973 | 79.959 | 79.971 | 79.947 | 79.949 | 79.960 | 0.026 |
| 23 | 79.920 | 79.961 | 79.937 | 79.935 | 79.934 | 79.937 | 0.041 |
| 24 | 79.937 | 79.934 | 79.931 | 79.934 | 79.964 | 79.940 | 0.033 |
| 25 | 79.945 | 79.954 | 79.957 | 79.935 | 79.961 | 79.950 | 0.026 |
| | | | | Average (X double bar) | | 79.951 | 0.040 |

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

$$R = \max\{x_1, x_2, \ldots x_n\} - \min\{x_1, x_2, \ldots x_n\}$$

$$\bar{\bar{X}} = \frac{\bar{X}_1 + \bar{X}_2 + \ldots + \bar{X}_t}{t}$$

# Defining the UCL and LCL

- Objective: Set UCL and LCL such that we can claim with 99.7% confidence that the process has "gone out of control," if we observe $\bar{X}$ or R outside the control limits

$$UCL = \bar{X} + (3 \times ESD\ \bar{X})$$

$$LCL = \bar{X} - (3 \times ESD\ \bar{X})$$

$$ESD\ \bar{X} = \frac{\hat{\sigma}}{\sqrt{n}}$$

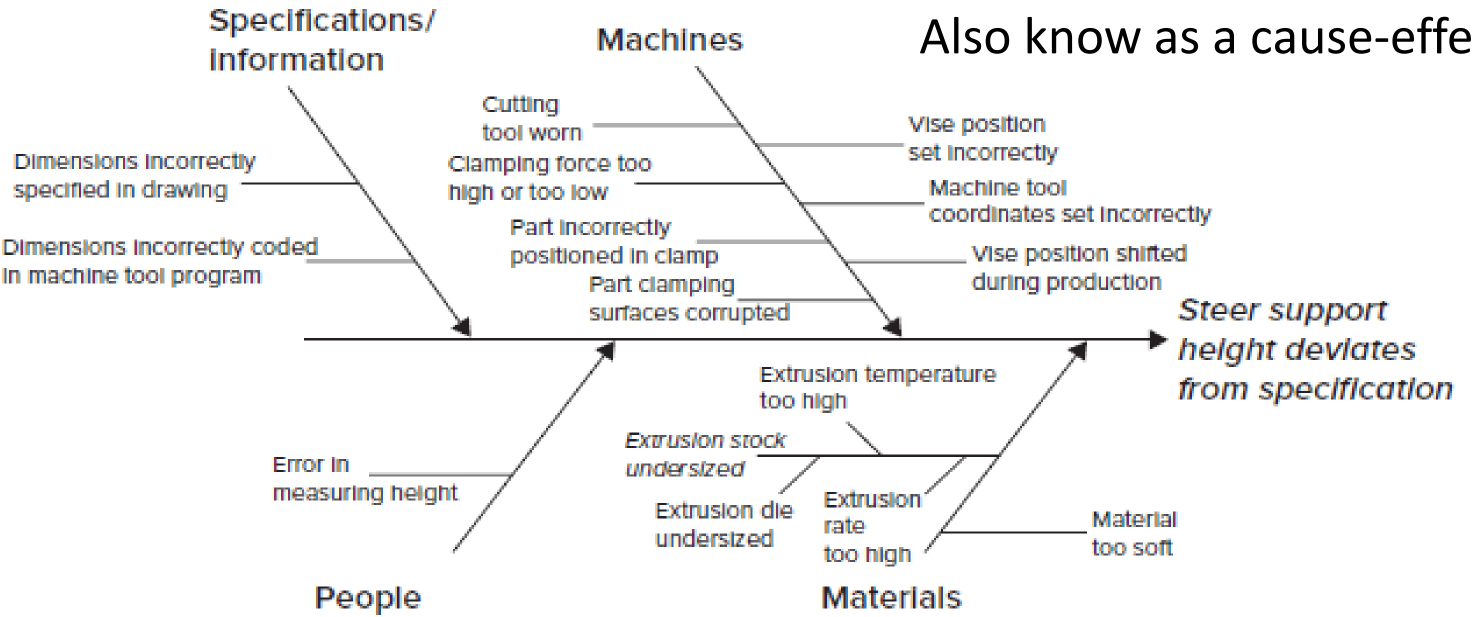
- $\hat{\sigma}$ = Estimated standard deviation based on all sample observation from all days
- If a process "goes out of control", we say an assignable cause has occurred with a 99.7% probability

# 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 an assignable cause variation has occurred
  - Our job to look for what input or environmental variables led to this result – to investigate the root cause for the abnormal variation
- First step- to create a more careful diagram illustrating the relationship between the outcome variable and the various input and environmental variables.

# Fishbone/Ishikava Diagram

A structured way to brainstorm about the potential root causes that have led to a change in an outcome variable. This is done by mapping out all input and environmental variables. Also know as a cause-effect diagram.

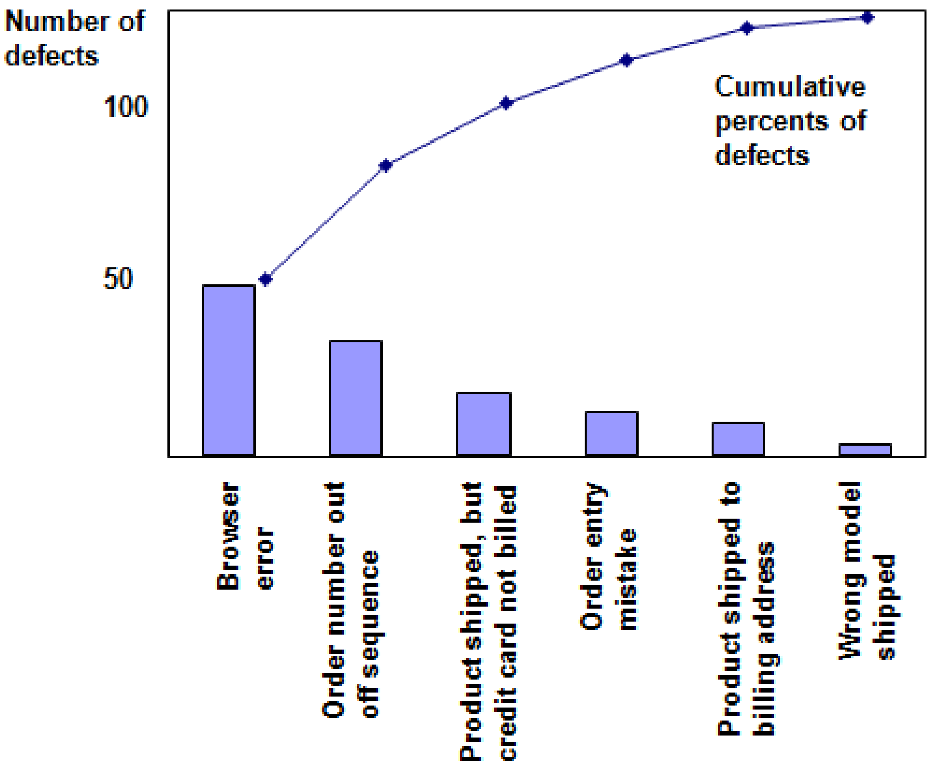


# Investigating Assignable Causes with the Five Whys Technique

- Brainstorming technique that helps employees to find the root cause of a problem by asking the question "Why" at least five times:
- Avoids stopping too early and not having found the real root cause.
- An example of a problem is: The vehicle will not start.
  - ***Why?*** – The battery is dead. (First why)
  - ***Why?*** – The alternator is not functioning. (Second why)
  - ***Why?*** – The alternator belt has broken. (Third why)
  - ***Why?*** – The alternator belt was well beyond its useful service life and not replaced. (Fourth why)
  - ***Why?*** – The vehicle was not maintained according to the recommended service schedule. (Fifth why, a root cause)

# Investigating Assignable Causes: Pareto Analysis

- Graphical way to identify the most important causes of process defects
- Order root causes in decreasing order of frequency of occurrence
- 80-20 logic

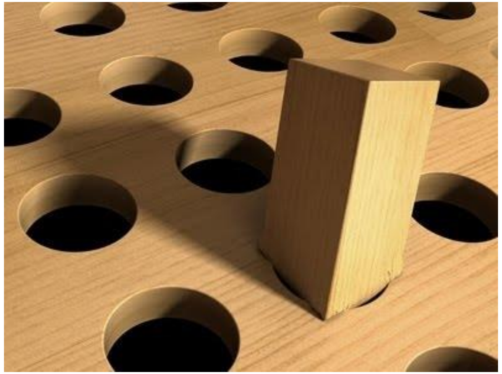



Given the multiple potential root causes of a defect (uncovered by the Fishbone/Five Whys technique) it is desirable to find the root cause for most of the problems.

# How to Eliminate Assignable Causes

- Design robust processes
  Robust processes can tolerate variation in input variables and environmental variables without leading to a defect. They are resistant against variation in input and environmental strategies.
- How can we make a process robust?
  - Over engineering – make the process so that can do well, even under exceptional conditions
  - Early warning signs on input and environmental variables There typically exists some lag time between the occurrence of a variation at this point an alert would be placed providing for earlier intervention to the root cause of the variation
  - Fool-proofing – Change the work in such a way that the operator cannot complete the task if s mistake has been made. The side benefit provides the operator feedback thus reducing the likelihood of future reoccurrence of defective outputs.

# Foolproofing (Poka-yoke)



# EXTRA

# Probability of Error Table Solution

$$z\text{-}Transformation : z = \frac{X - \mu}{\sigma}$$

- LSL: 79.900 mm
- USL: 80.000 mm
- Height of the steer support:
  - Standard deviation σ = 0.017291 mm
  - Mean μ = 79.950 mm.
- Pr(Height < 79.900 mm)?

$$z = \frac{79.900 - 79.950}{0.017291} = -2.8918$$

**Standard Normal Distribution Function Table, ϕ(z)|$F_{(0,1)}$(z)**

| z | -0.09 | -0.08 | -0.07 | -0.06 | -0.05 | -0.04 | -0.03 | -0.02 | -0.01 | 0.00 |
|---|---|---|---|---|---|---|---|---|---|---|
| -3.9 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| -3.8 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| -3.7 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| -3.6 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0002 | 0.0002 |
| -3.5 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0002 |
| -3.4 | 0.0002 | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 0.0003 |
| -3.3 | 0.0003 | 0.0004 | 0.0004 | 0.0004 | 0.0004 | 0.0004 | 0.0004 | 0.0005 | 0.0005 | 0.0005 |
| -3.2 | 0.0005 | 0.0005 | 0.0005 | 0.0006 | 0.0006 | 0.0006 | 0.0006 | 0.0006 | 0.0007 | 0.0007 |
| -3.1 | 0.0007 | 0.0007 | 0.0008 | 0.0008 | 0.0008 | 0.0008 | 0.0009 | 0.0009 | 0.0009 | 0.0010 |
| -3.0 | 0.0010 | 0.0010 | 0.0011 | 0.0011 | 0.0011 | 0.0012 | 0.0012 | 0.0013 | 0.0013 | 0.0013 |
| -2.9 | 0.0014 | 0.0014 | 0.0015 | 0.0015 | 0.0016 | 0.0016 | 0.0017 | 0.0018 | 0.0018 | 0.0019 |
| -2.8 | 0.0019 | 0.0020 | 0.0021 | 0.0021 | 0.0022 | 0.0023 | 0.0023 | 0.0024 | 0.0025 | 0.0026 |
| -2.7 | 0.0026 | 0.0027 | 0.0028 | 0.0029 | 0.0030 | 0.0031 | 0.0032 | 0.0033 | 0.0034 | 0.0035 |
| -2.6 | 0.0036 | 0.0037 | 0.0038 | 0.0039 | 0.0040 | 0.0041 | 0.0043 | 0.0044 | 0.0045 | 0.0047 |
| -2.5 | 0.0048 | 0.0049 | 0.0051 | 0.0052 | 0.0054 | 0.0055 | 0.0057 | 0.0059 | 0.0060 | 0.0062 |
| -2.4 | 0.0064 | 0.0066 | 0.0068 | 0.0069 | 0.0071 | 0.0073 | 0.0075 | 0.0078 | 0.0080 | 0.0082 |
| -2.3 | 0.0084 | 0.0087 | 0.0089 | 0.0091 | 0.0094 | 0.0096 | 0.0099 | 0.0102 | 0.0104 | 0.0107 |
| -2.2 | 0.0110 | 0.0113 | 0.0116 | 0.0119 | 0.0122 | 0.0125 | 0.0129 | 0.0132 | 0.0136 | 0.0139 |
| -2.1 | 0.0143 | 0.0146 | 0.0150 | 0.0154 | 0.0158 | 0.0162 | 0.0166 | 0.0170 | 0.0174 | 0.0179 |
| -2.0 | 0.0183 | 0.0188 | 0.0192 | 0.0197 | 0.0202 | 0.0207 | 0.0212 | 0.0217 | 0.0222 | 0.0228 |

$$\Pr\{Height \leq 79.900\ mm\} = 0.0019$$

# Probability of Error Table Solution

$$z\text{-}Transformation : z = \frac{X - \mu}{\sigma}$$

- LSL: 79.900 mm
- USL: 80.000 mm
- Height of the steer support:
  - Standard deviation σ = 0.017291 mm
  - Mean μ = 79.950 mm.
- Pr(Height > 80.000 mm)?

$$z = \frac{80.000 - 79.950}{0.017291} = 2.8918$$

**Standard Normal Distribution Function Table, ϕ(z)|F(0,1)(z)**

| z | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 |
|---|---|---|---|---|---|---|---|---|---|---|
| 2.0 | 0.9772 | 0.9778 | 0.9783 | 0.9788 | 0.9793 | 0.9798 | 0.9803 | 0.9808 | 0.9812 | 0.9817 |
| 2.1 | 0.9821 | 0.9826 | 0.9830 | 0.9834 | 0.9838 | 0.9842 | 0.9846 | 0.9850 | 0.9854 | 0.9857 |
| 2.2 | 0.9861 | 0.9864 | 0.9868 | 0.9871 | 0.9875 | 0.9878 | 0.9881 | 0.9884 | 0.9887 | 0.9890 |
| 2.3 | 0.9893 | 0.9896 | 0.9898 | 0.9901 | 0.9904 | 0.9906 | 0.9909 | 0.9911 | 0.9913 | 0.9916 |
| 2.4 | 0.9918 | 0.9920 | 0.9922 | 0.9925 | 0.9927 | 0.9929 | 0.9931 | 0.9932 | 0.9934 | 0.9936 |
| 2.5 | 0.9938 | 0.9940 | 0.9941 | 0.9943 | 0.9945 | 0.9946 | 0.9948 | 0.9949 | 0.9951 | 0.9952 |
| 2.6 | 0.9953 | 0.9955 | 0.9956 | 0.9957 | 0.9959 | 0.9960 | 0.9961 | 0.9962 | 0.9963 | 0.9964 |
| 2.7 | 0.9965 | 0.9966 | 0.9967 | 0.9968 | 0.9969 | 0.9970 | 0.9971 | 0.9972 | 0.9973 | 0.9974 |
| 2.8 | 0.9974 | 0.9975 | 0.9976 | 0.9977 | 0.9977 | 0.9978 | 0.9979 | 0.9979 | 0.9980 | 0.9981 |
| 2.9 | 0.9981 | 0.9982 | 0.9982 | 0.9983 | 0.9984 | 0.9984 | 0.9985 | 0.9985 | 0.9986 | 0.9986 |
| 3.0 | 0.9987 | 0.9987 | 0.9987 | 0.9988 | 0.9988 | 0.9989 | 0.9989 | 0.9989 | 0.9990 | 0.9990 |
| 3.1 | 0.9990 | 0.9991 | 0.9991 | 0.9991 | 0.9992 | 0.9992 | 0.9992 | 0.9992 | 0.9993 | 0.9993 |
| 3.2 | 0.9993 | 0.9993 | 0.9994 | 0.9994 | 0.9994 | 0.9994 | 0.9994 | 0.9995 | 0.9995 | 0.9995 |
| 3.3 | 0.9995 | 0.9995 | 0.9995 | 0.9996 | 0.9996 | 0.9996 | 0.9996 | 0.9996 | 0.9996 | 0.9997 |
| 3.4 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9998 |
| 3.5 | 0.9998 | 0.9998 | 0.9998 | 0.9998 | 0.9998 | 0.9998 | 0.9998 | 0.9998 | 0.9998 | 0.9998 |
| 3.6 | 0.9998 | 0.9998 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 0.9999 |
| 3.7 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 0.9999 |
| 3.8 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 0.9999 |
| 3.9 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |

$$\Pr\{Height \leq 80.000\ mm\} = 0.9981$$
$$\Pr\{Height > 80.000\ mm\} = 1 - 0.9981 = 0.0019$$

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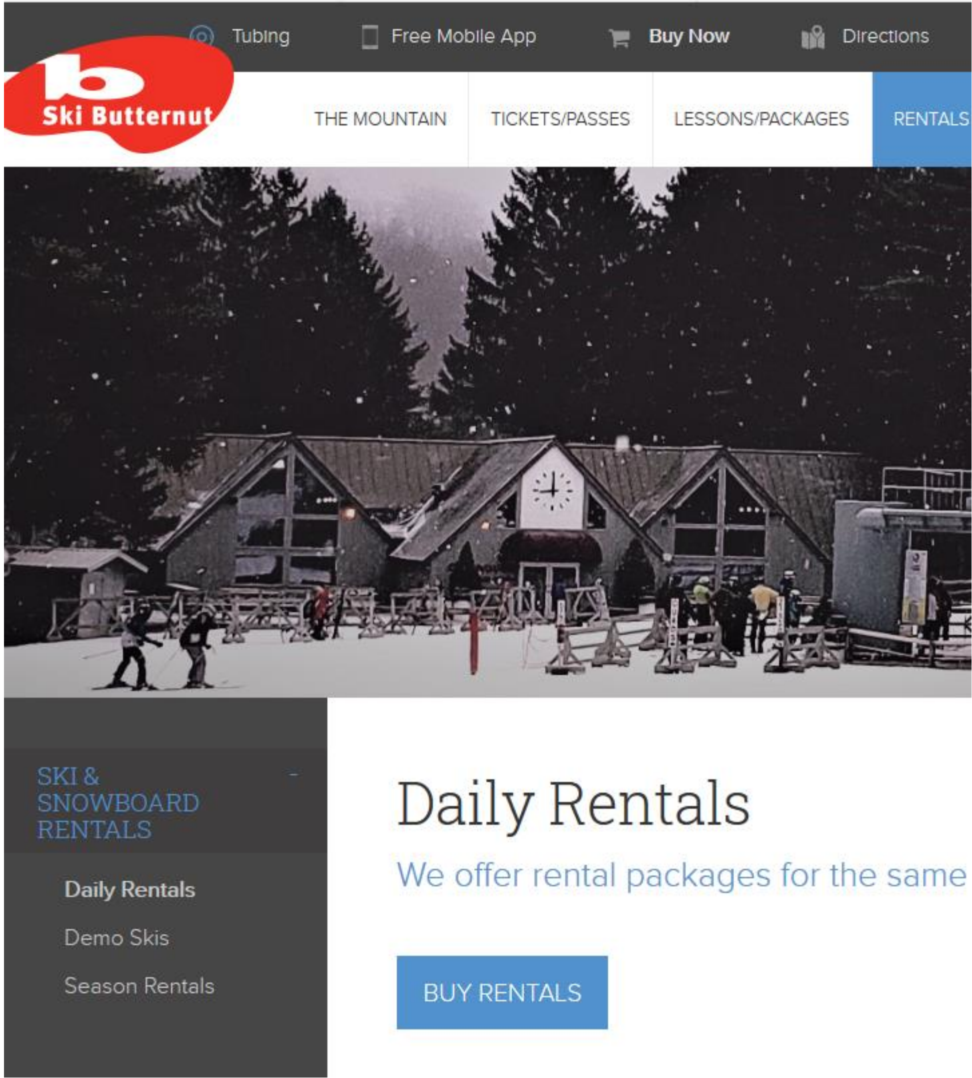
# 2023
# Operations Management

# SERVICE SYSTEMS WITH PATIENT CUSTOMERS

# QUEUES WHEN DEMAND EXCEEDS SUPPLY

# Ski Butternut Rental Shop

- Small ski resort in Berkshire Mountains of eastern Massachusetts
- 10 lifts, 22 trails
- 1 rental shop

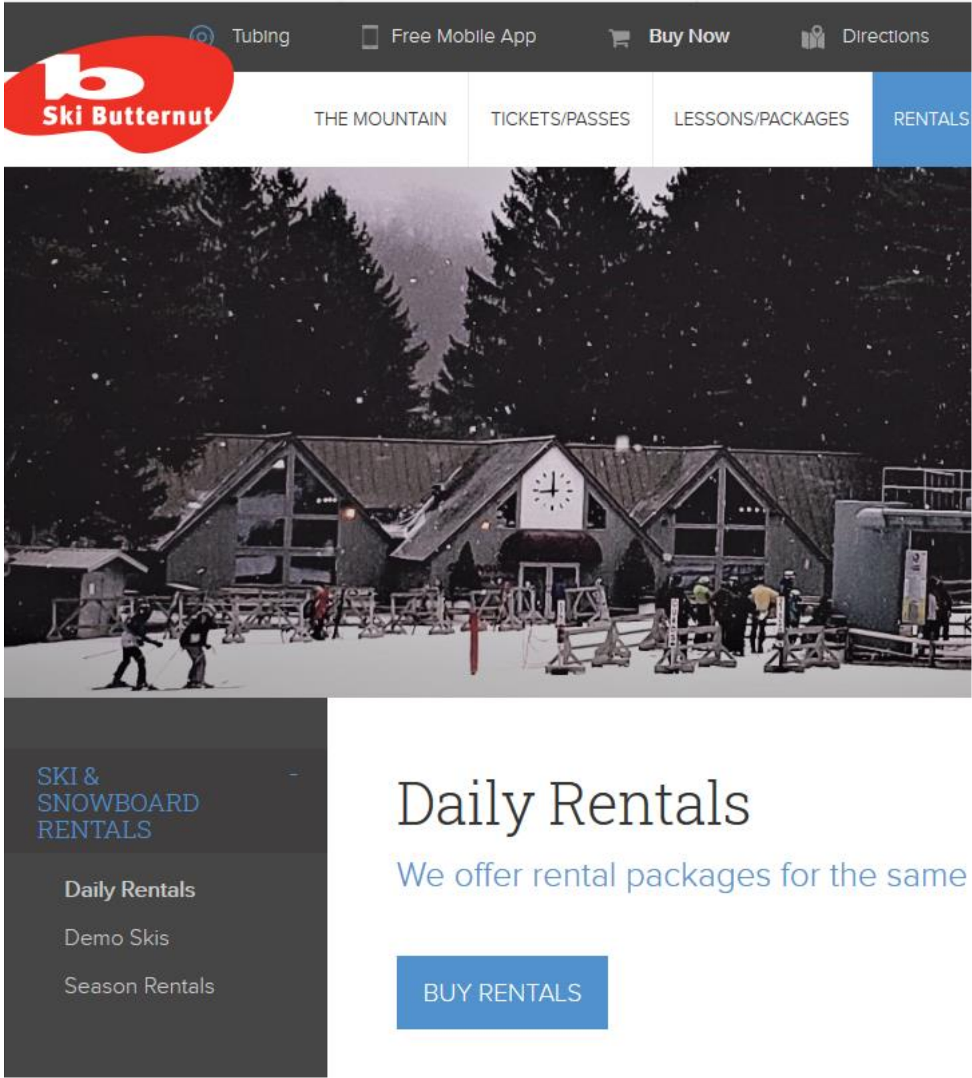





https://skibutternut.com/rentals/

# Ski Butternut Rental Shop Challenges

- What is the maximum length of the queue at the shop?
- How long does a customer have to wait?
- What is the average customer wait time?
- How can peak demand be managed?

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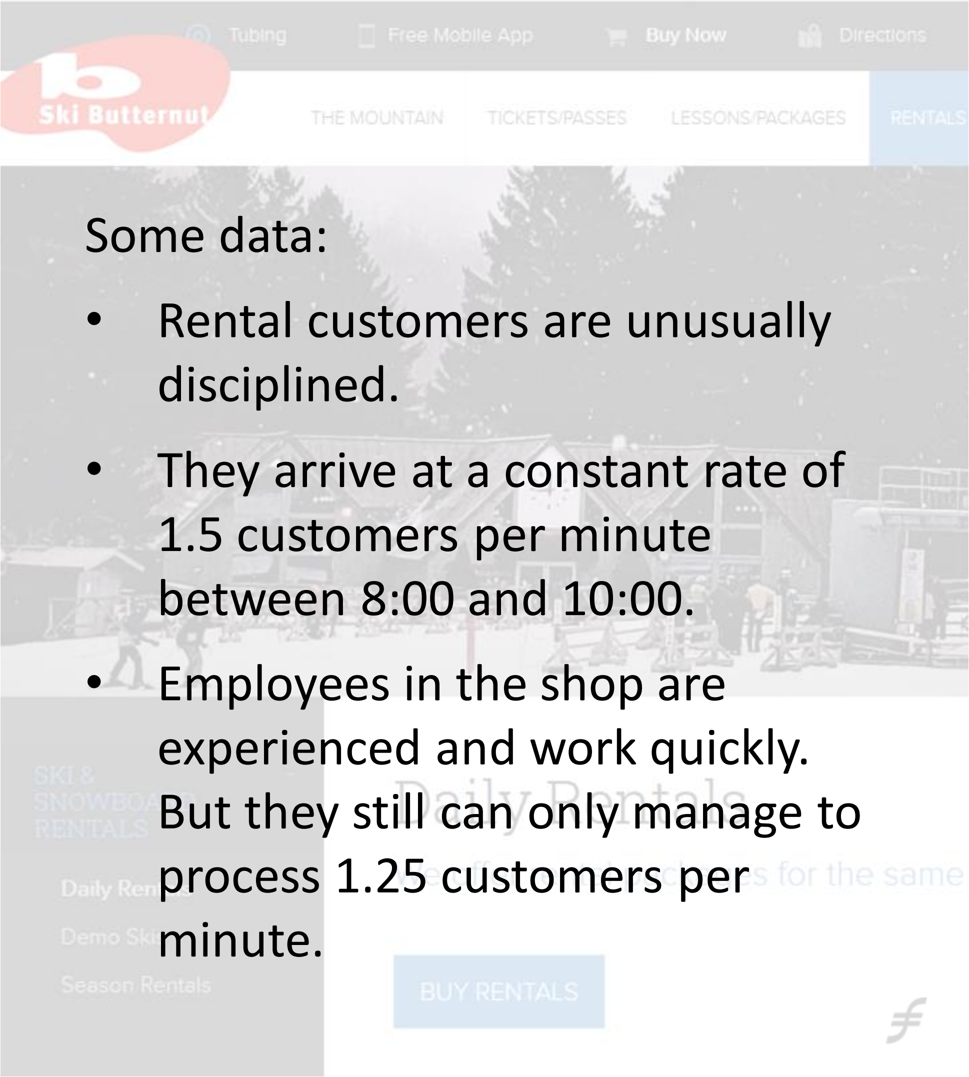


Some data:

- Rental customers are unusually disciplined.
- They arrive at a constant rate of 1.5 customers per minute between 8:00 and 10:00.
- Employees in the shop are experienced and work quickly. But they still can only manage to process 1.25 customers per minute.

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# Maximum Length of the Queue

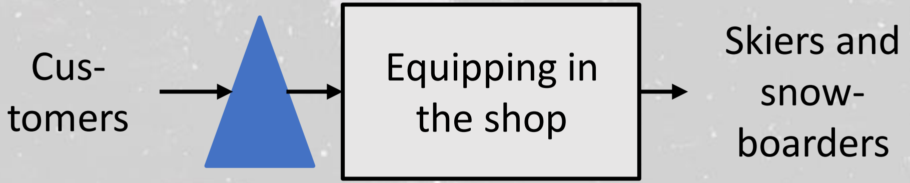
- Rental shop queue growth rate

$$= 1.5 \frac{cust.}{min} - 1.25 \frac{cust.}{min}$$
$$= 0.25 \frac{cust.}{min}$$

- Length of queue when last customer arrives

$$= 120min \cdot 0.25 \frac{cust.}{min}$$
$$= 30\ cust.$$

Process flow diagram




$$\begin{matrix} Queue \\ growth\ rate \end{matrix} = Demand - Capacity$$

$$\begin{matrix} Length\ of \\ queue \\ at\ time\ T \end{matrix} = T \cdot Queue\ growth\ rate$$



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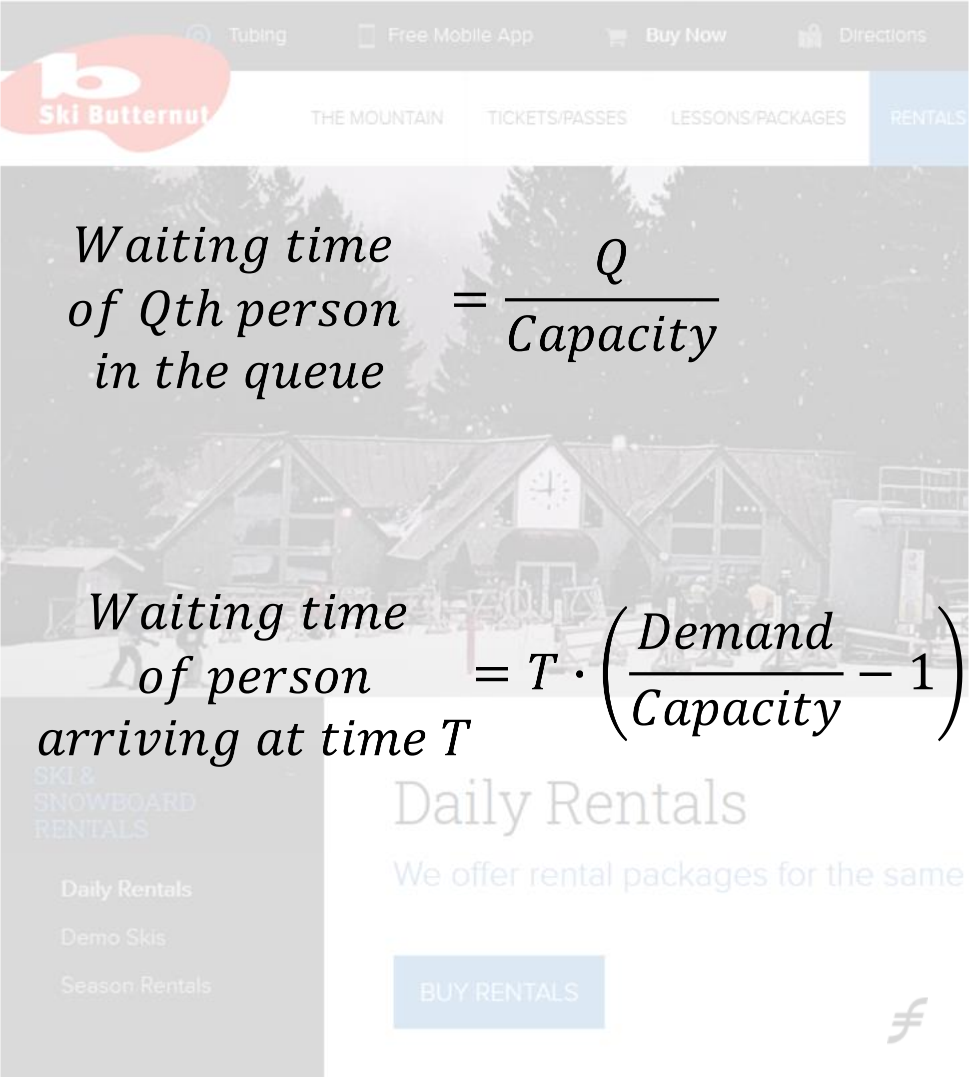
# How long does a customer wait?

- Waiting time of last customer arriving (30th in the queue):

$$= \frac{30\ cust.}{1.25\,\frac{cust.}{min}} = 24min$$

- Alternatively:

$$= 120min \cdot \left( \frac{1.5\,\frac{cust.}{min}}{1.25\,\frac{cust.}{min}} - 1 \right)$$




$$\begin{array}{c} Waiting\ time \\ of\ Qth\ person \\ in\ the\ queue \end{array} = \frac{Q}{Capacity}$$

$$\begin{array}{c} Waiting\ time \\ of\ person \\ arriving\ at\ time\ T \end{array} = T \cdot \left( \frac{Demand}{Capacity} - 1 \right)$$



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# Ski Butternut Rental Shop Challenges

- What is the maximum length of the queue at the shop?
- How long does a customer have to wait?
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- How can peak demand be managed?

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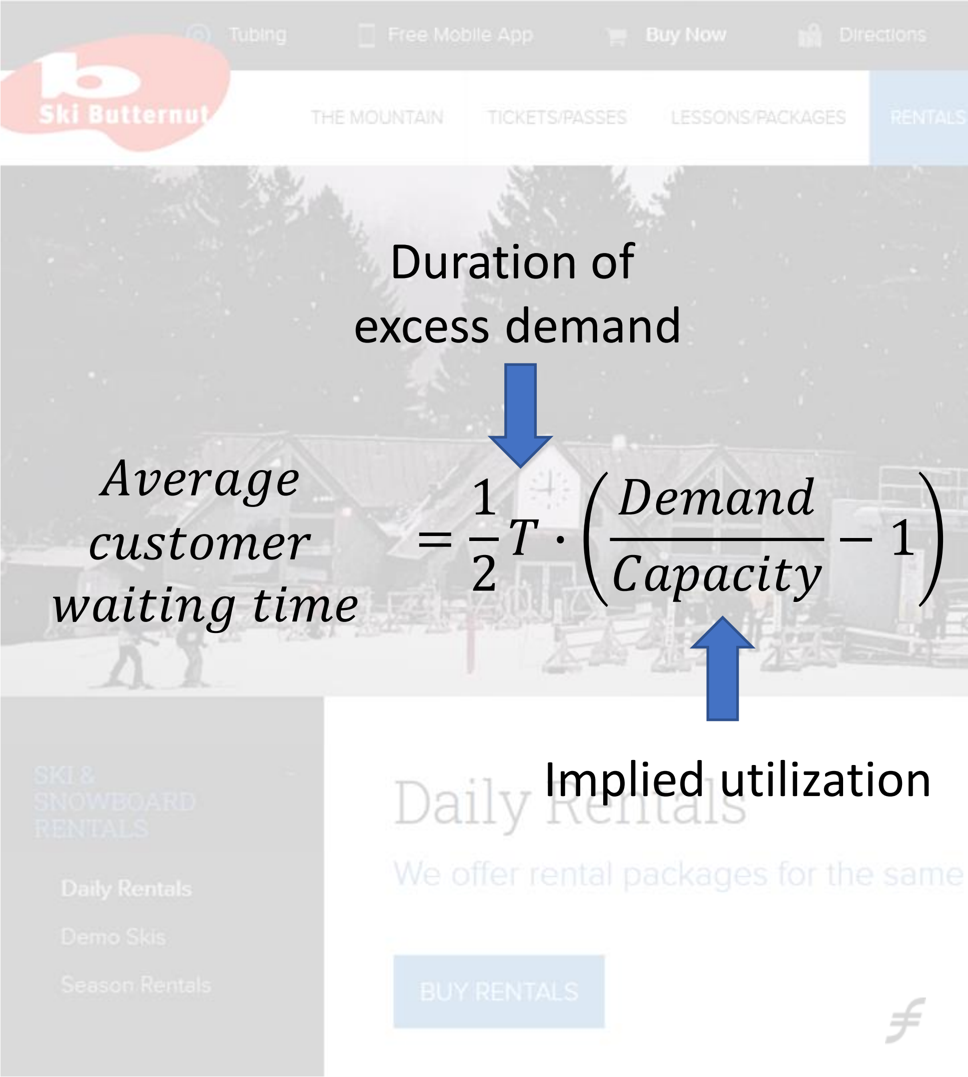
# How long does the average customer wait?

- Average customer waiting time

$$= \frac{1}{2} 120\, min \cdot \left( \frac{1.5 \frac{cust.}{min}}{1.25 \frac{cust.}{min}} - 1 \right)$$

$$= 12\, min$$




Duration of excess demand

$$\textit{Average customer waiting time} = \frac{1}{2} T \cdot \left( \frac{Demand}{Capacity} - 1 \right)$$

Implied utilization



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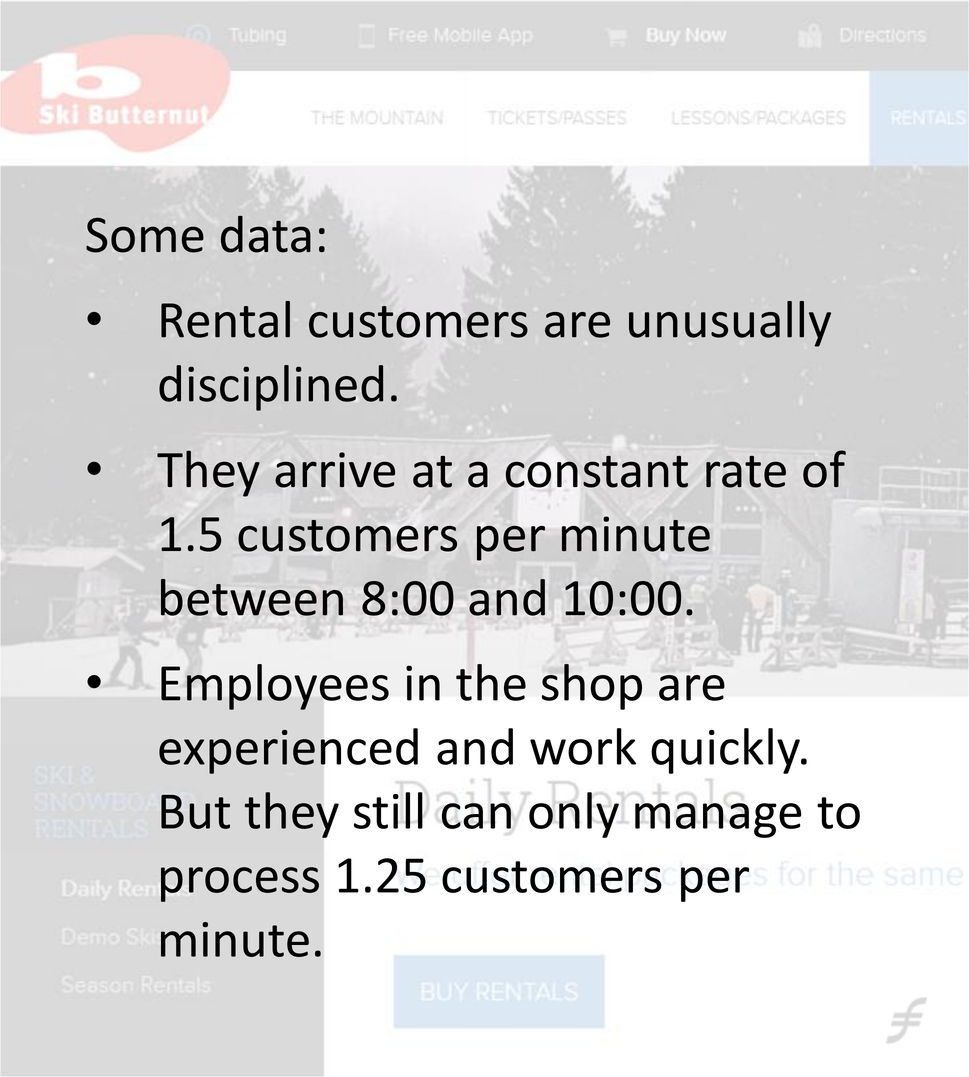
# Ski Butternut Rental Shop Challenges

- What the maximum length of the queue at the shop?
- How long does a customers have to wait?
- What is the average customer wait time?
- **How can peak demand be managed?**

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- Employees in the shop are experienced and work quickly. But they still can only manage to process 1.25 customers per minute.

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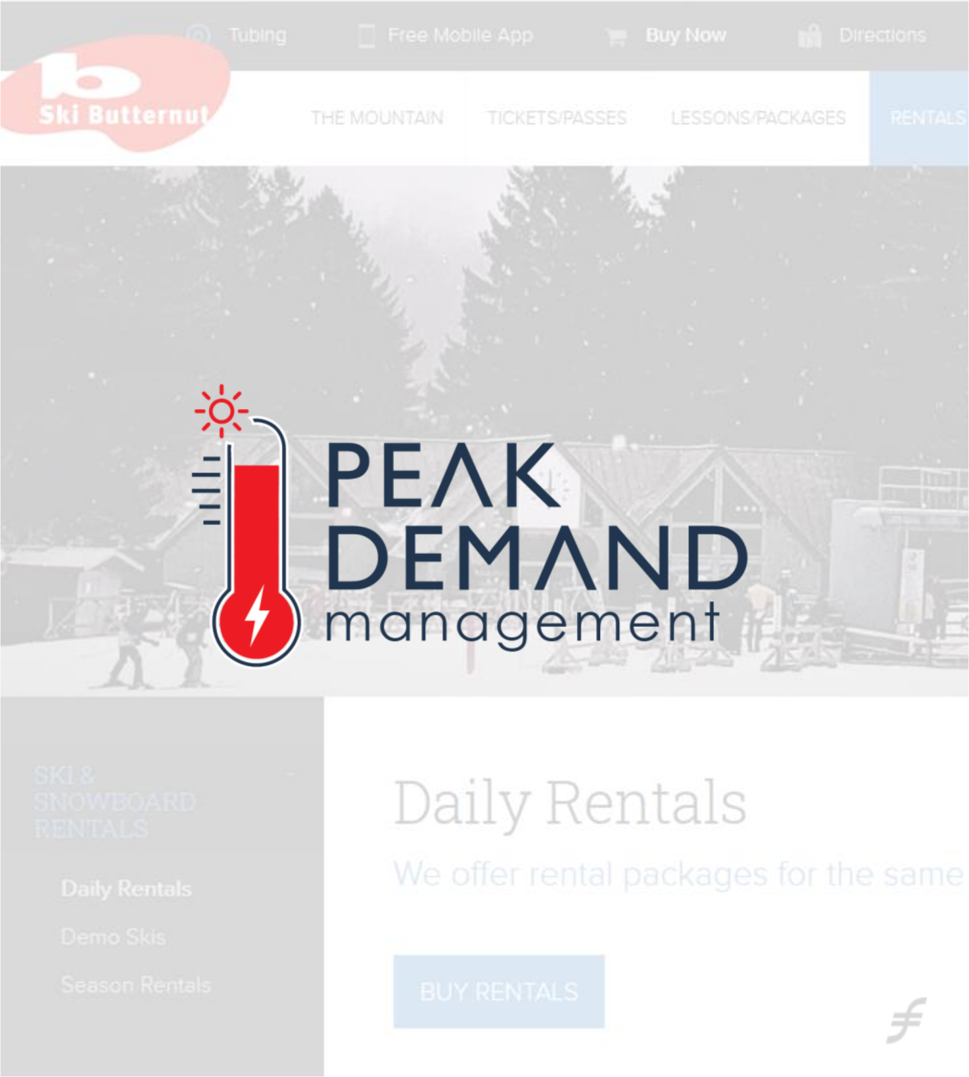
# Managing Peak Demand

- Reduce peak demand by
  - Peak-load pricing
  - Off-peak discount

- Increase capacity
  - Increase resources
  - Pre-processing





https://skibutternut.com/rentals/

# QUEUES WHEN DEMAND AND SUPPLY ARE VARIABLE - ONE SERVER

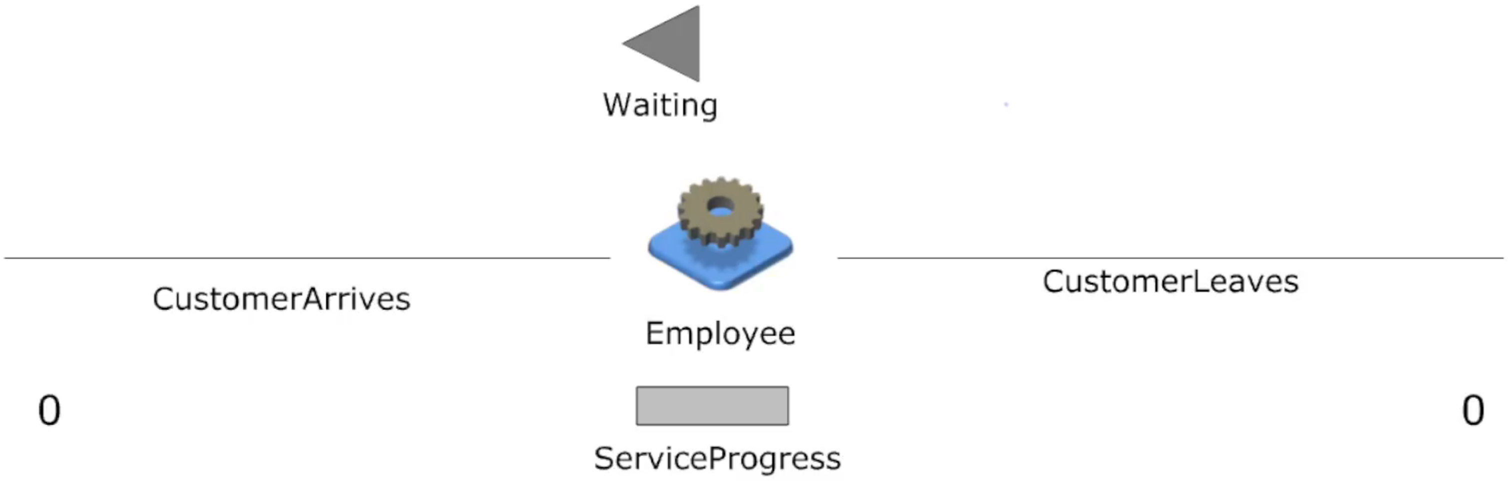
# Frankfurt Key Services

- Primary address for copying keys
- Opening hours: 9:00 to 19:00
- Many years of experience, highest precision, large selection of blanks
- Fast: full copy in 4 minutes on average

**Frankfurt Key Service**

10:00 to 11:00 on a typical day

*09:55:00.000*



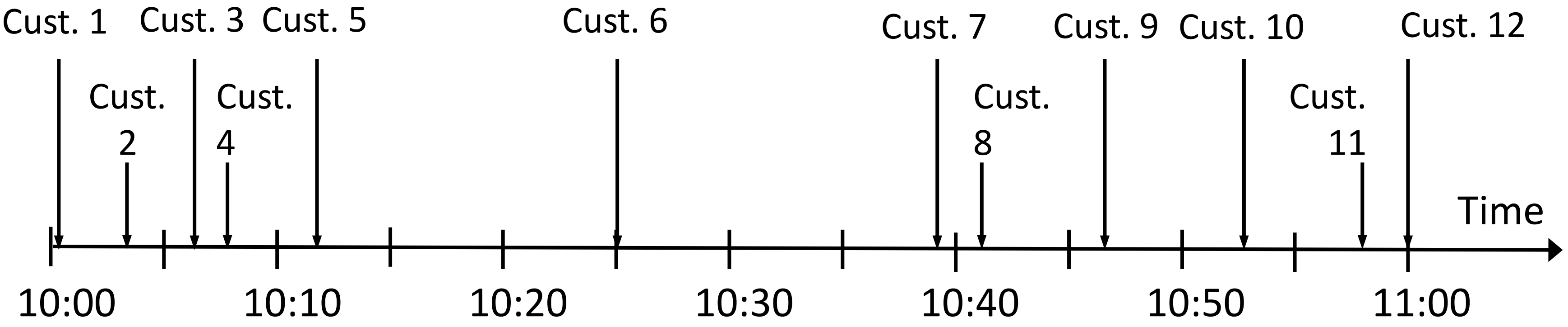
# Key Services Challenges

- What is the capacity?
- How long do customers have to wait on average?
- How many customers wait on average in or in front of the shop?

# Key Services Challenges

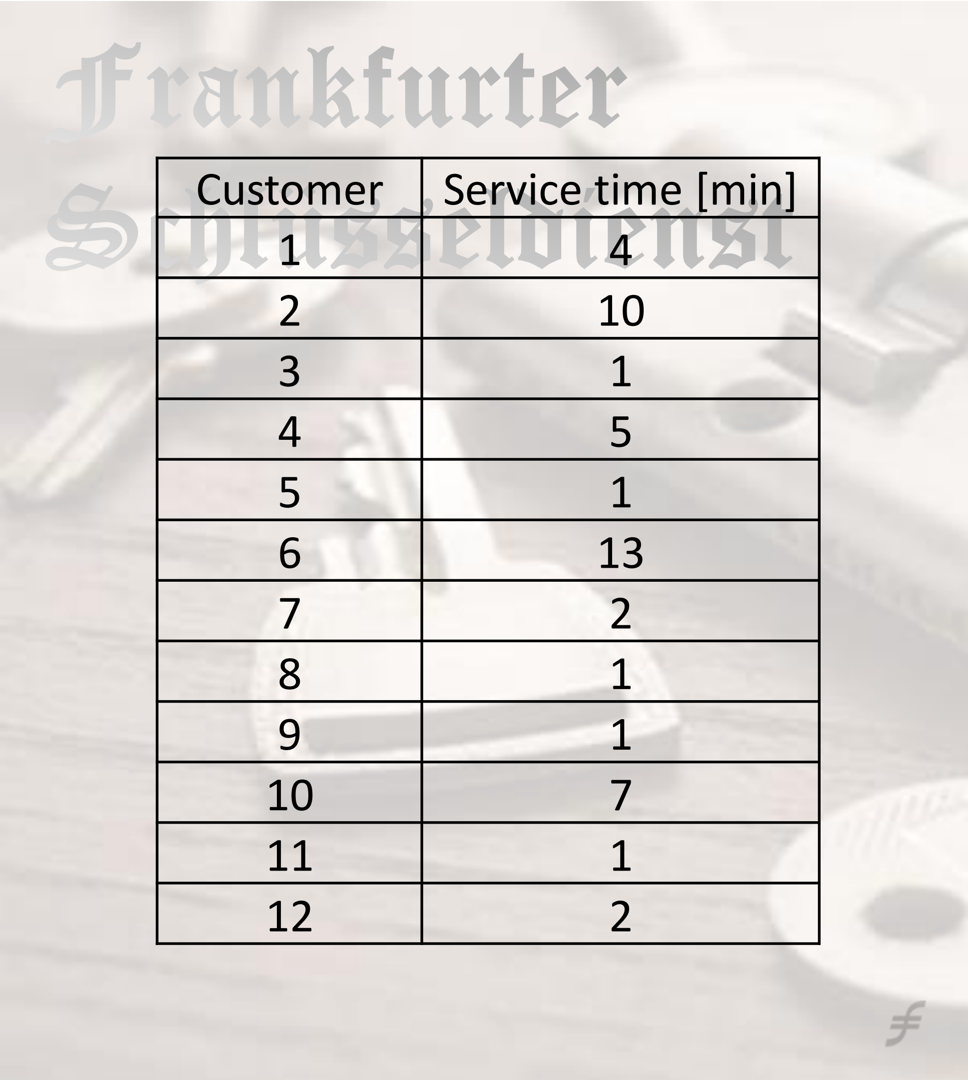
- **What is the capacity?**
- How long do customers have to wait on average?
- How many customers wait on average in or in front of the shop?

# Key Service: Arrival and Operating Data




| Customer | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Customer Arrival Time | 10:01 | 10:04 | 10:06 | 10:07 | 10:11 | 10:28 | 10:40 | 10:41 | 10:46 | 10:53 | 10:59 | 11:00 |
| Service Time [min] | 4 | 10 | 1 | 5 | 1 | 13 | 2 | 1 | 1 | 7 | 1 | 2 |

# Capacity of Frankfurter Schlüsseldienst




| Customer | Service time [min] |
|---|---|
| 1 | 4 |
| 2 | 10 |
| 3 | 1 |
| 4 | 5 |
| 5 | 1 |
| 6 | 13 |
| 7 | 2 |
| 8 | 1 |
| 9 | 1 |
| 10 | 7 |
| 11 | 1 |
| 12 | 2 |

# Key Services Challenges

- What is the capacity?
- **How long do customers have to wait on average?**
- How many customers wait on average in or in front of the shop?

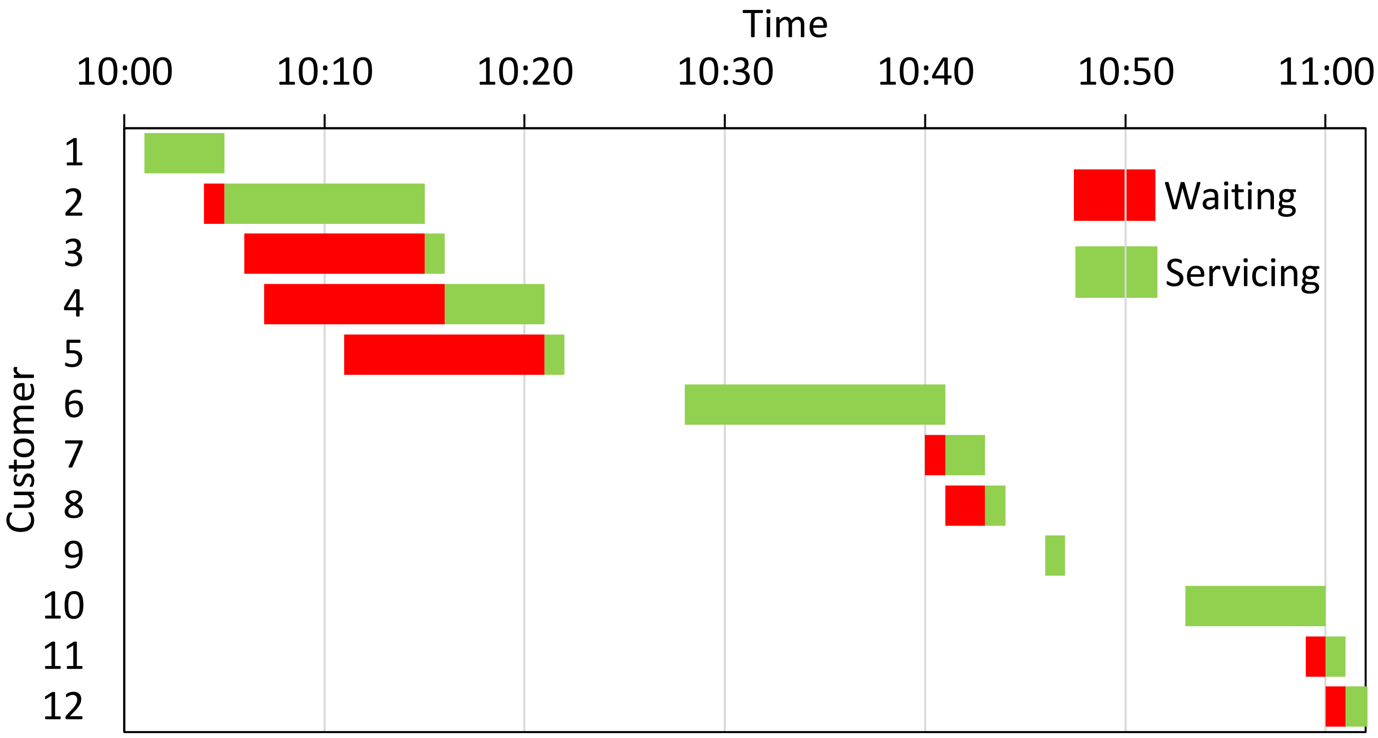

- one employee serves
- customers wait patiently

# Calculation of Waiting Times

| Cust. | Customer arrival time | Service time | Start time of service | End time of service | Waiting time |
|---|---|---|---|---|---|
| 1 | 10:01 | 04:00 | | | |
| 2 | 10:04 | 10:00 | | | |
| 3 | 10:06 | 01:00 | | | |
| 4 | 10:07 | 05:00 | 10:16 | 10:21 | 00:09 |
| 5 | 10:11 | 01:00 | 10:21 | 10:22 | 00:10 |
| 6 | 10:28 | 13:00 | 10:28 | 10:41 | 00:00 |
| 7 | 10:40 | 02:00 | 10:41 | 10:43 | 00:01 |
| 8 | 10:41 | 01:00 | 10:43 | 10:44 | 00:02 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |

in[hh:mm]

# Waiting and Service Times as Gantt-Diagram



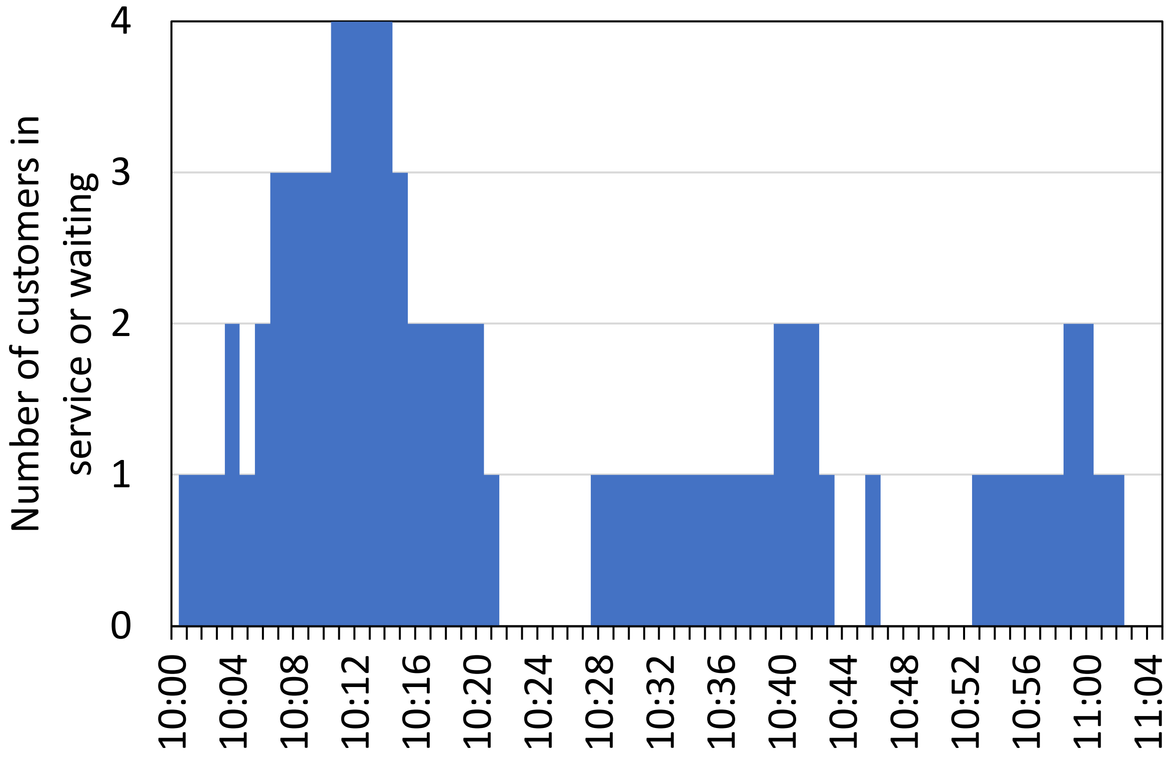

| Waiting Time | [mm:ss] |
|---|---|
| Total | 34:00 |
| Min | 00:00 |
| Max | 10:00 |
| Average | 02:50 |

# Key Services Challenges

- What is the capacity?
- How long do customers have to wait on average?
- **How many customers wait on average in or in front of the shop?**


- one employee serves
- customers wait patiently

# Number of Customers C (either Waiting or in Service)




On average:

10:00 to 11:02

$\rightarrow$ 63 min

$$\varnothing C = \frac{\sum_{t=1}^{63} C_t}{63}$$

$$= 1.3016\ [Customers]$$

# tel-inform Inbound Call Center

- Modern, owner-managed service company with around 300 employees
- Three defining pillars: tradition, social commitment and humanity
- Excellent customer service, e.g. for tax consultants



https://www.tel-inform.de/

# tel-inform Inbound Call Center Challenges

In a system with variability in customer arrivals and processing and with limited availability of past data,

- what is the (average) flow rate?
- what is the (average) flow time? (waiting plus processing time)
- what is the (average) inventory? (number of customers waiting and in service)

## tel-inform call center data

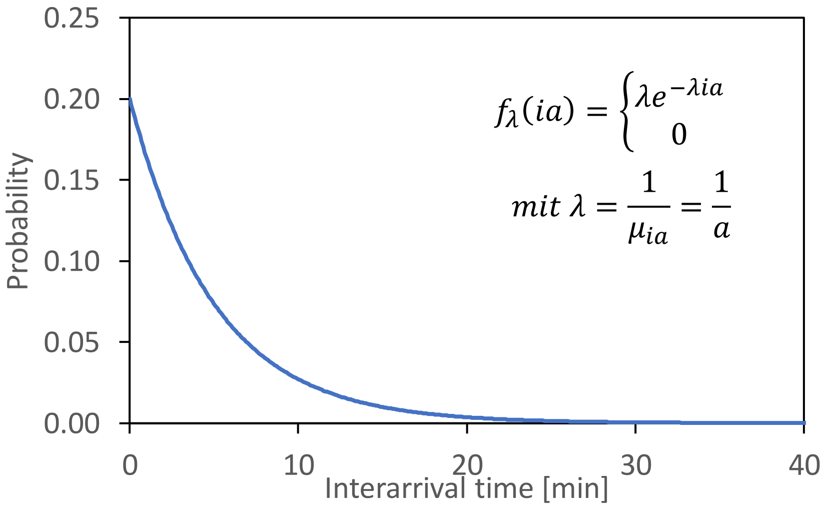
$1\ employee$

$avg\ service\ time\ p = 4\ min$
$(uniformly\ distributed\ between\ 2\ and\ 6\ min)$

$$avg\ arrival\ rate = 12\ \frac{calls}{h}$$

$avg\ interarrival\ time\ a =$

$exponentially\ distributed\ interarrival\ times\ ia$:



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# tel-inform Average Flow Rate

$$Demand\ rate = average\ \ inflow\ rate$$
$$= average\ arrival\ rate$$

$$Flow\ rate =$$
$$min\begin{Bmatrix} Demand\ rate, \\ Process\ capacity \end{Bmatrix}$$

Variability in customer arrivals and processing…

…does **not** affect the calculation of the average flow rate!

…does **complicate** the calculation of the average flow time!

# tel-inform Inbound Call Center Challenges

In a system with variability in customer arrivals and processing and with limited availability of past data,

- what is the (average) flow rate?
- what is the (average) flow time? (waiting plus processing time)
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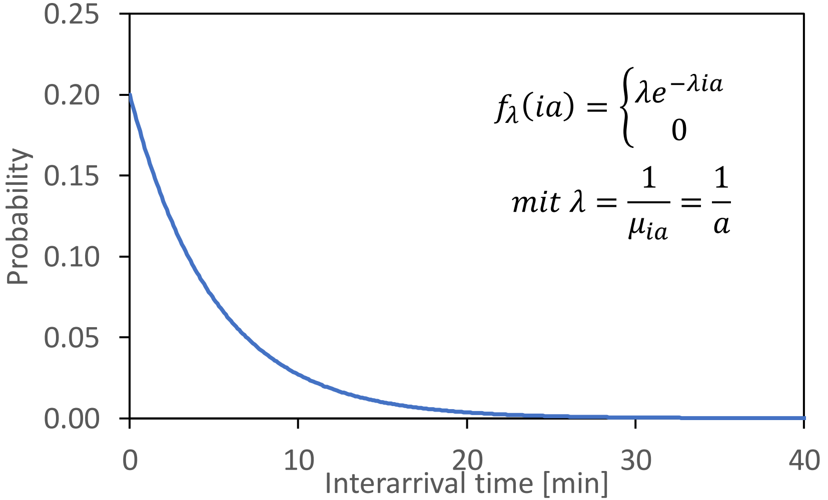




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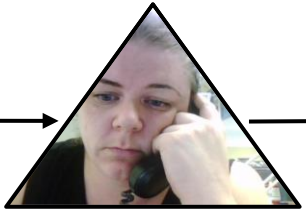
# tel-inform Process Flow Diagram and Data (6:00 to 7:00)

$12\ \frac{calls}{h}$

Inflow rate



m = 1

$12\ \frac{calls}{h}$

Outflow rate

(no losses)

Time

Entry to system

Begin service

Departure

**Wanted:**

**Flow time**

**T = ?**

**Waiting (flow)**

**time Tq = ?**

Service (flow)

time p = 4 min

# One Server Waiting Time Formula

$$Flow\ Time\ T = T_q + p$$

We know p (service flow time), but we need the following waiting formula to calculate Tq:

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

$CV_a^2$: $Coefficient\ of\ variation\ of\ the\ interarrvial\ time\ a$

$CV_p^2$: $Coefficient\ of\ variation\ of\ the\ processing\ time\ p$

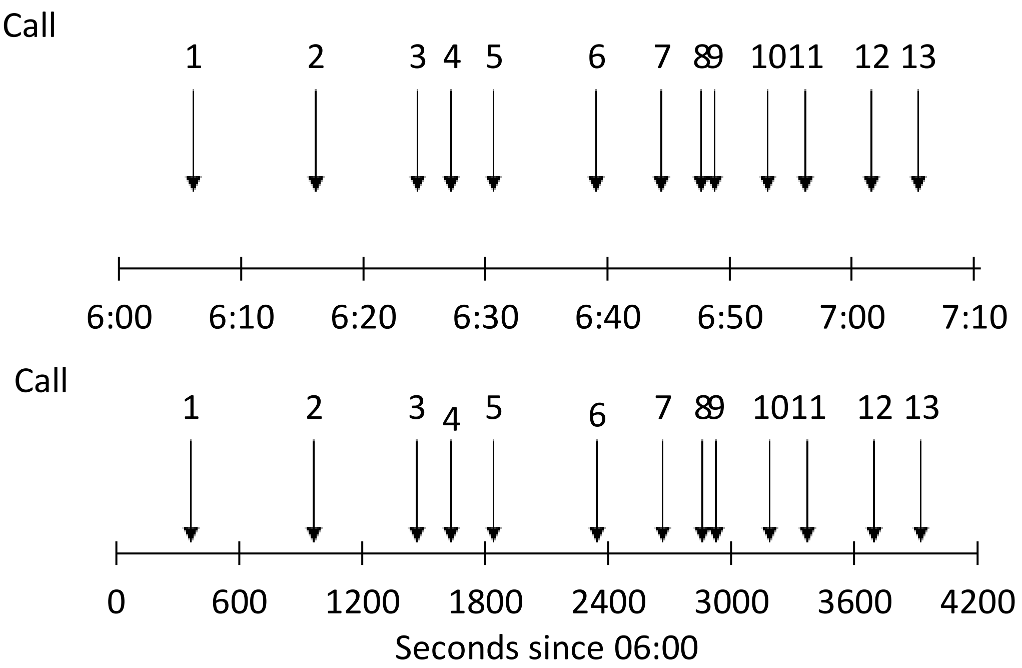
$$Coefficient\ of\ variation\ CV = \frac{Standard\ deviation}{Mean}$$

# Requirements of the Waiting Time Formula

- Constant average arrival rates
- Server utilization < 100%
- Exponentially distributed interarrival times
- Arbitrarily distributed service times

# Interarrival Time vs Arrival Time

| Call | Call arrival time [hh:mm:ss] | Interarrival time [s] |
|---|---|---|
| 1 | 06:06:05 | |
| 2 | 06:16:06 | 00:10:01 |
| 3 | 06:24:27 | 00:08:21 |
| 4 | 06:27:15 | 00:02:48 |
| 5 | 06:30:42 | 00:03:27 |
| 6 | 06:39:05 | 00:08:23 |
| 7 | 06:44:27 | 00:05:22 |
| 8 | 06:47:42 | 00:03:15 |
| 9 | 06:48:46 | 00:01:04 |
| 10 | 06:53:08 | 00:04:23 |
| 11 | 06:56:13 | 00:03:05 |
| 12 | 07:01:38 | 00:05:25 |
| 13 | 07:05:27 | 00:03:48 |




a is the average interarrival time!

# How to Determine $CV_a$ at tel-inform?

- Way 1: Based on the empirical observation that interarrival times are typically exponentially distributed
  - For an exponential distribution, it can be shown that mean = standard deviation
  - Therefore, $CV_a = 1$
- Way 2: Based on data
  - Using sample mean $\bar{x}$ as estimator of the population mean
  - Using sample standard deviation s as estimator of the population standard deviation

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \quad \text{or Excel function } STDEV.S$$

# How to Determine $CV_p$ at tel-inform?

- Way 1: Use prior knowledge about the probability distribution type and parameters
  - tel-inform service time p is uniformly distributed between 2 and 6 min

$$\mu = \frac{upper\ bound + lower\ bound}{2} =$$

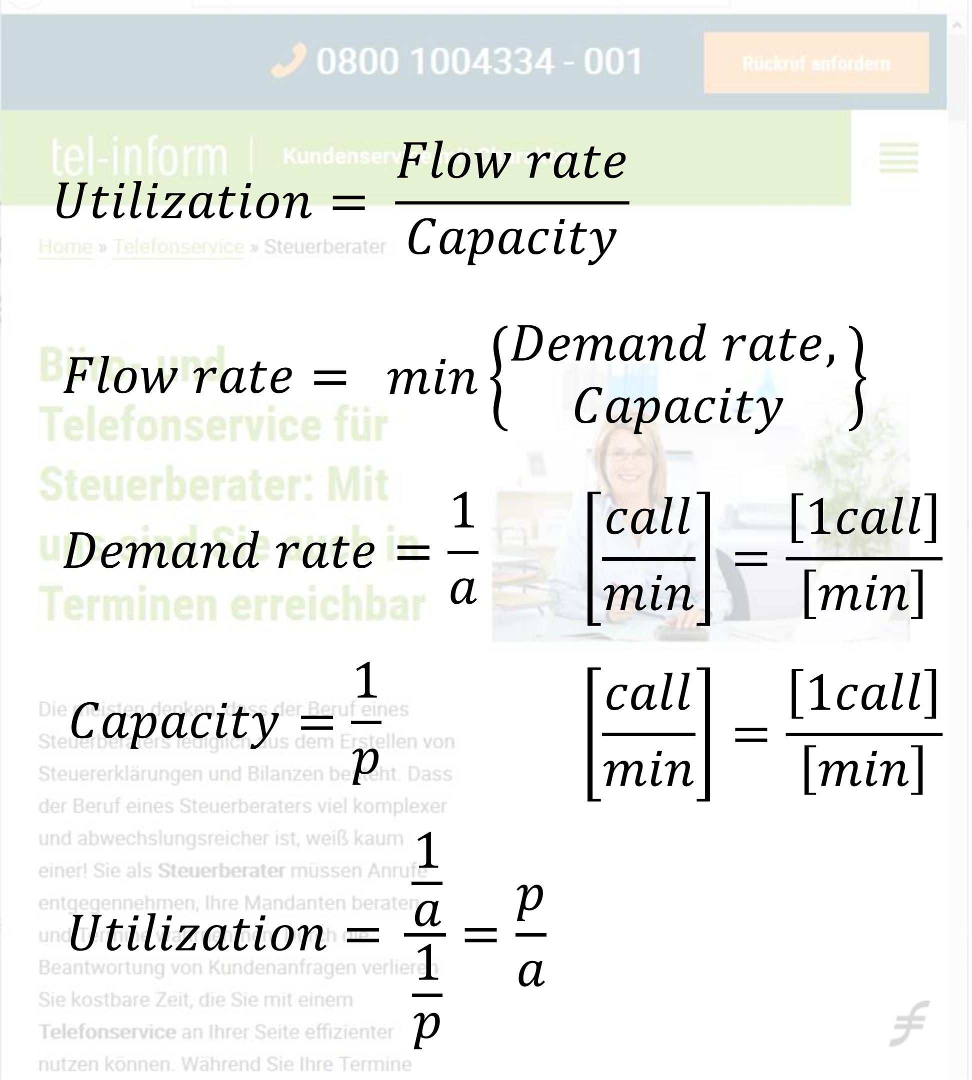
$$\sigma = \sqrt{\frac{(upper\ bound\ - lower\ bound)^2}{12}} =$$

$$CV_p = \frac{\sigma}{\mu} =$$

- Way 2: Based on data (see way 2 for $CV_a$)

# Utilization at tel-inform?

$$Utilization =$$




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

$$Flow\ rate = \min\left\{\begin{matrix} Demand\ rate, \\ Capacity \end{matrix}\right\}$$

$$Demand\ rate = \frac{1}{a} \quad \left[\frac{call}{min}\right] = \frac{[1call]}{[min]}$$

$$Capacity = \frac{1}{p} \quad \left[\frac{call}{min}\right] = \frac{[1call]}{[min]}$$

$$Utilization = \frac{\frac{1}{a}}{\frac{1}{p}} = \frac{p}{a}$$

# Waiting time at tel-inform?

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

$$Utilization = 0.8000$$

$$CV_a = 1.000$$

$$CV_p = 0.2887$$

# tel-inform Inbound Call Center Challenges

In a system with variability in customer arrivals and processing and with limited availability of past data,

- what is the (average) flow rate?
- what is the (average) flow time? (waiting plus processing time)
- what is the (average) inventory? (number of customers waiting and in service)

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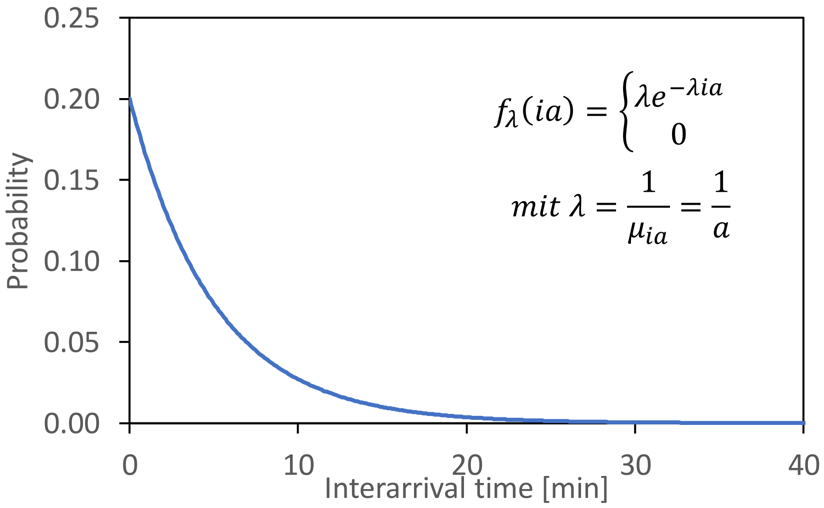
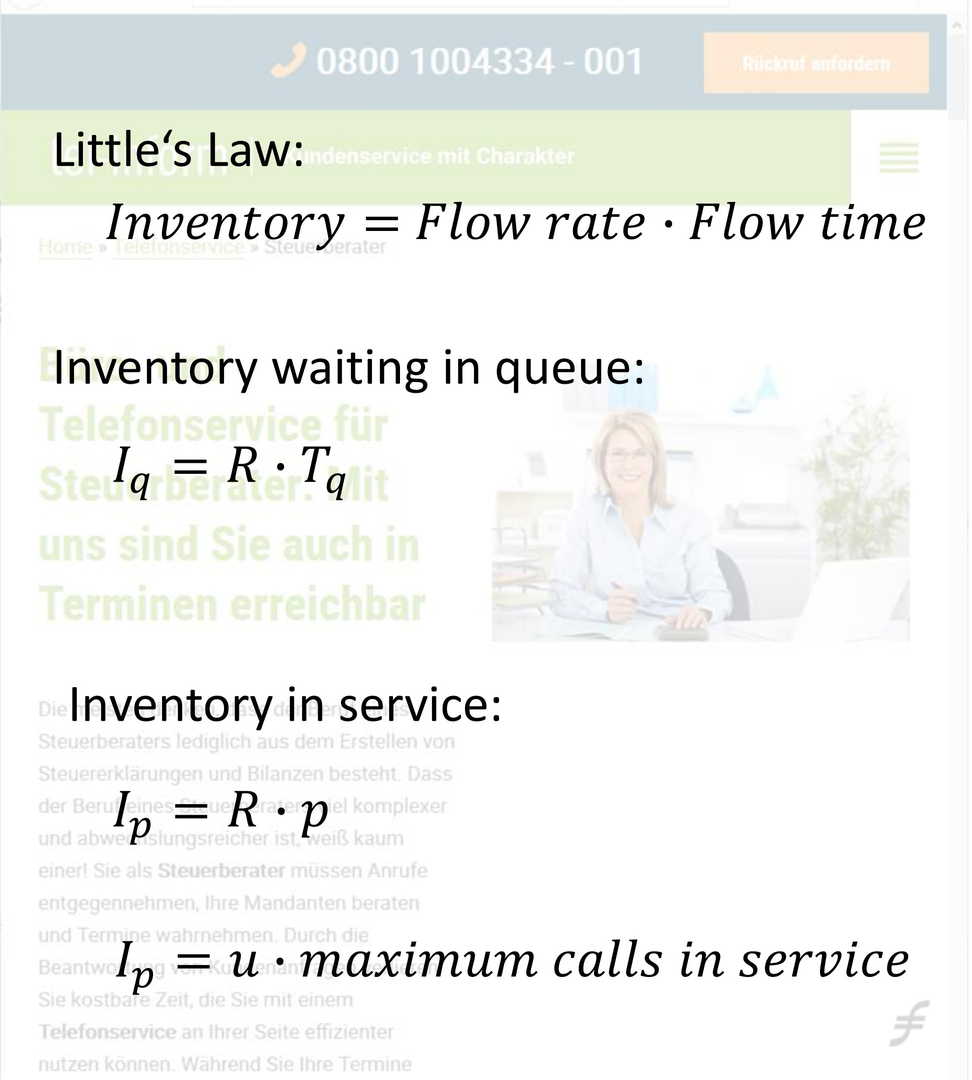





https://www.tel-inform.de/

# Average Inventory




Little's Law:

$$Inventory = Flow\ rate \cdot Flow\ time$$

Inventory waiting in queue:

$$I_q = R \cdot T_q$$

Inventory in service:

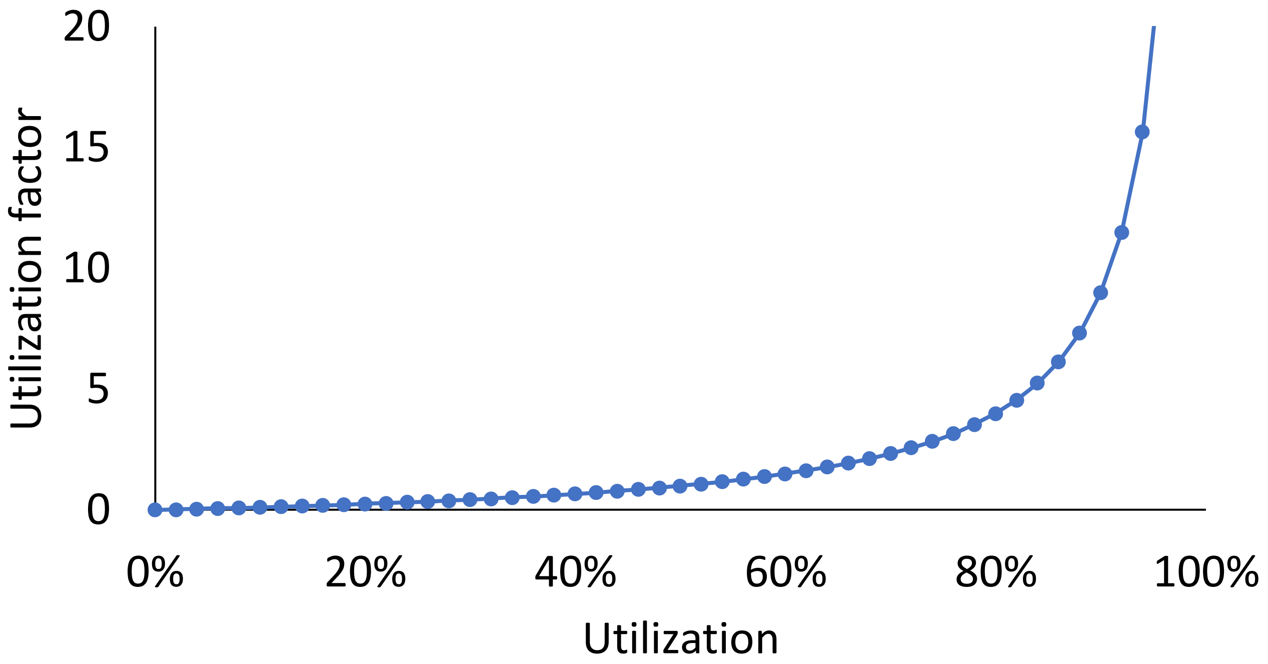
$$I_p = R \cdot p$$

$$I_p = u \cdot maximum\ calls\ in\ service$$

# The Key Drivers of Waiting Time

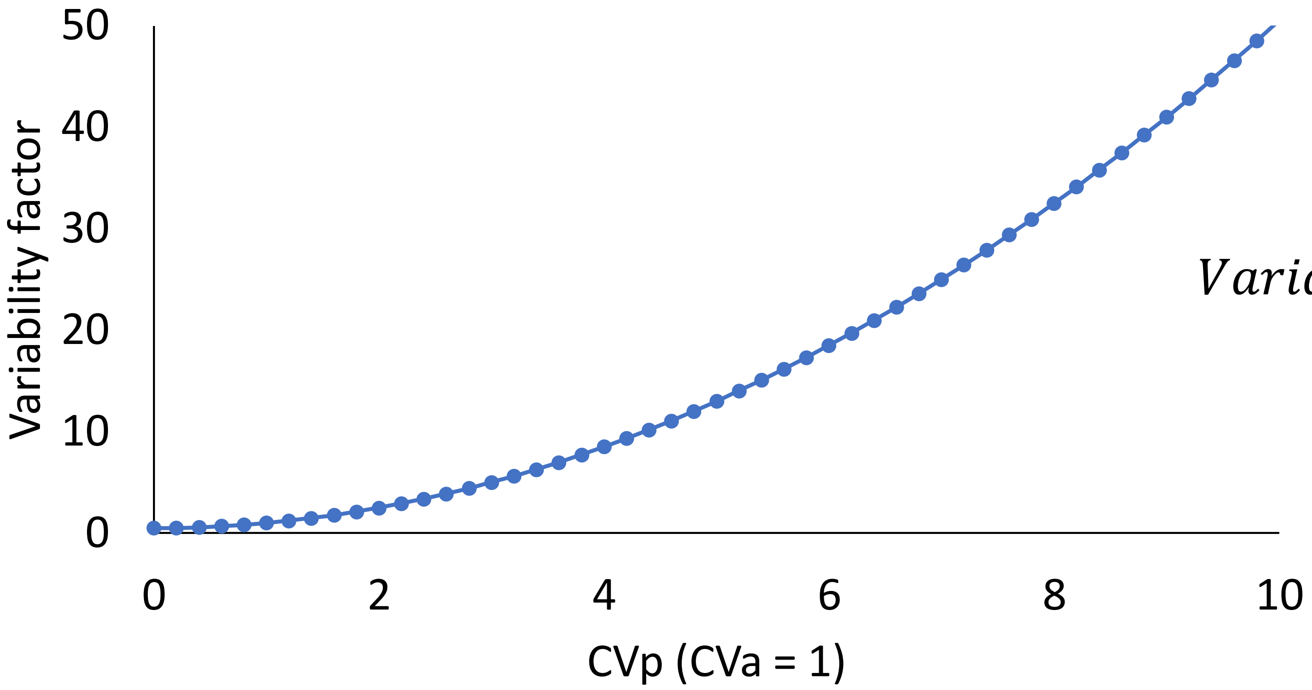
$$T_q = \underbrace{p}_{\text{Service time factor}} \cdot \underbrace{\left(\frac{Utilization}{1 - Utilization}\right)}_{\text{Utilization factor}} \cdot \underbrace{\left(\frac{{CV_a}^2 + {CV_p}^2}{2}\right)}_{\text{Variability factor}}$$

# Utilization Factor as Function of Utilization




$$Utilization\ factor = \frac{Utilization}{1 - Utilization}$$

# Variability Factor as Function of CVp




$$Variability\ factor = \frac{CV_a^2 + CV_p^2}{2}$$

# QUEUES WHEN DEMAND AND SUPPLY ARE VARIABLE - MULTIPLE SERVER

# Fraport Terminal 2 Challenges

How to organize the self-service check-in machines?

- Multiple machines with multiple queues (one per machine)?
- Multiple machines with one common queue?



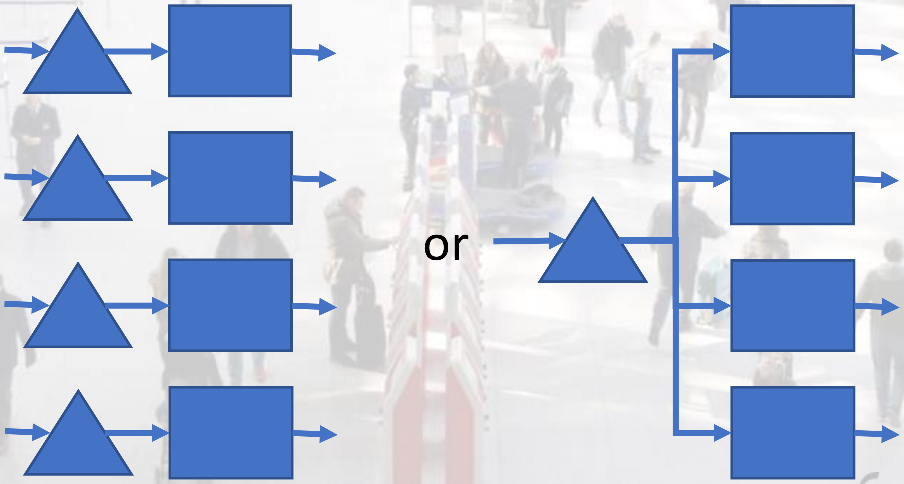

https://www.fraport.de/

# Fraport Terminal 2
# Challenges

How to organize the self-service check-in machines?

- Multiple machines with multiple queues (one per machine)?
- Multiple machines with one common queue?

- 4 self-service check-in machines
- p is exponentially distributed with a mean of 1 minute per passenger
- a is exponentially distributed with a mean of 1/3 minutes



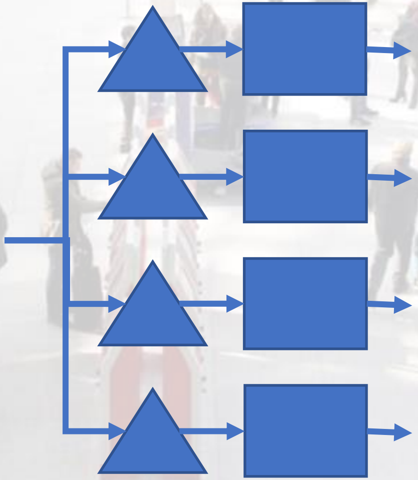



https://www.fraport.de/

# Self-service Check-in Machine Utilization

$$Utilization = \frac{p}{a \cdot m}$$

- 4 self-service check-in machines
- p is exponentially distributed with a mean of 1 minute per passenger
- a is exponentially distributed with a mean of 1/3 minutes
- Arriving passengers are split equally into four lines





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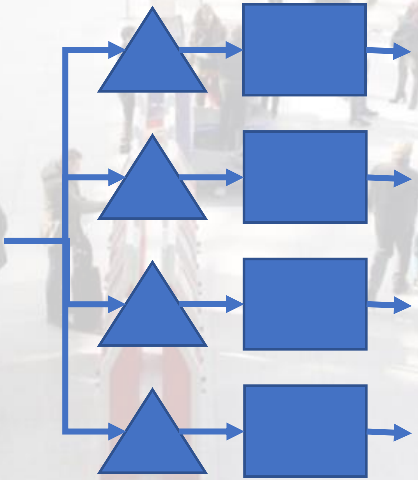
# Waiting Time in One of the Four Check-in Lines

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

# Number of Passengers Waiting in Line

$$I_q = R \cdot T_q$$

- 4 self-service check-in machines
- p is exponentially distributed with a mean of 1 minute per passenger
- a is exponentially distributed with a mean of 1/3 minutes
- Arriving passengers are split equally into four lines



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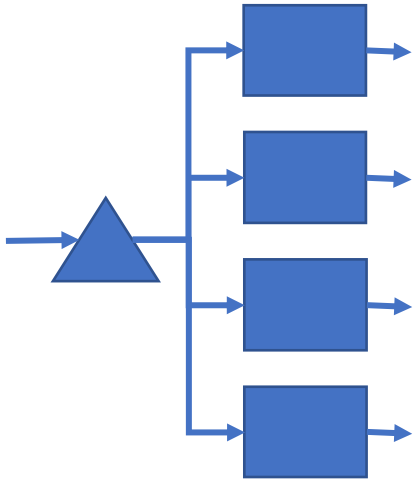
# Waiting Time in the Shared Check-in Line

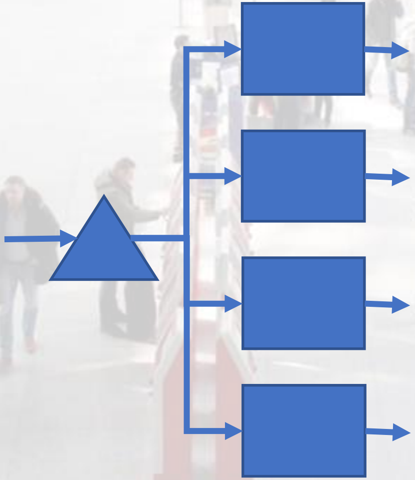
$$T_q = \frac{p}{m} \cdot \left( \frac{Utilization^{\sqrt{2(m+1)}-1}}{1 - Utilization} \right) \cdot \left( \frac{CV_a^2 + CV_p^2}{2} \right)$$



# Number of Passengers Waiting in the One Line

$$I_q = R \cdot T_q$$

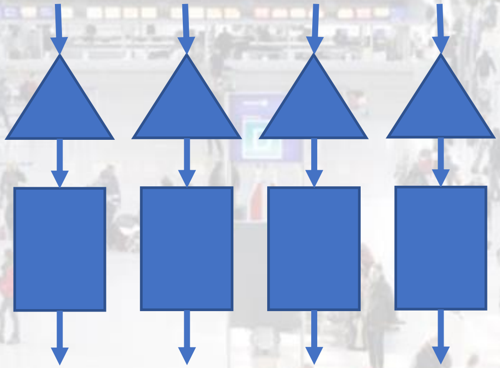
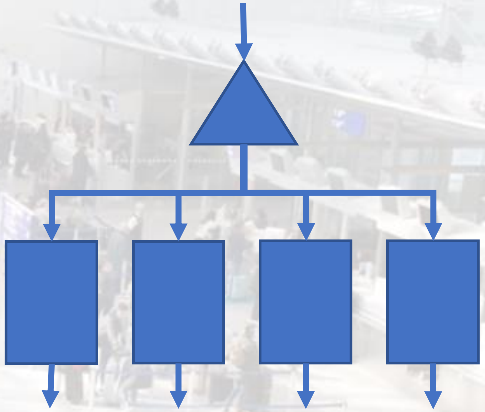
- 4 self-service check-in machines
- p is exponentially distributed with a mean of 1 minute
- a is exponentially distributed with a mean of 1/3 minutes
- Arriving passengers are split equally into four lines

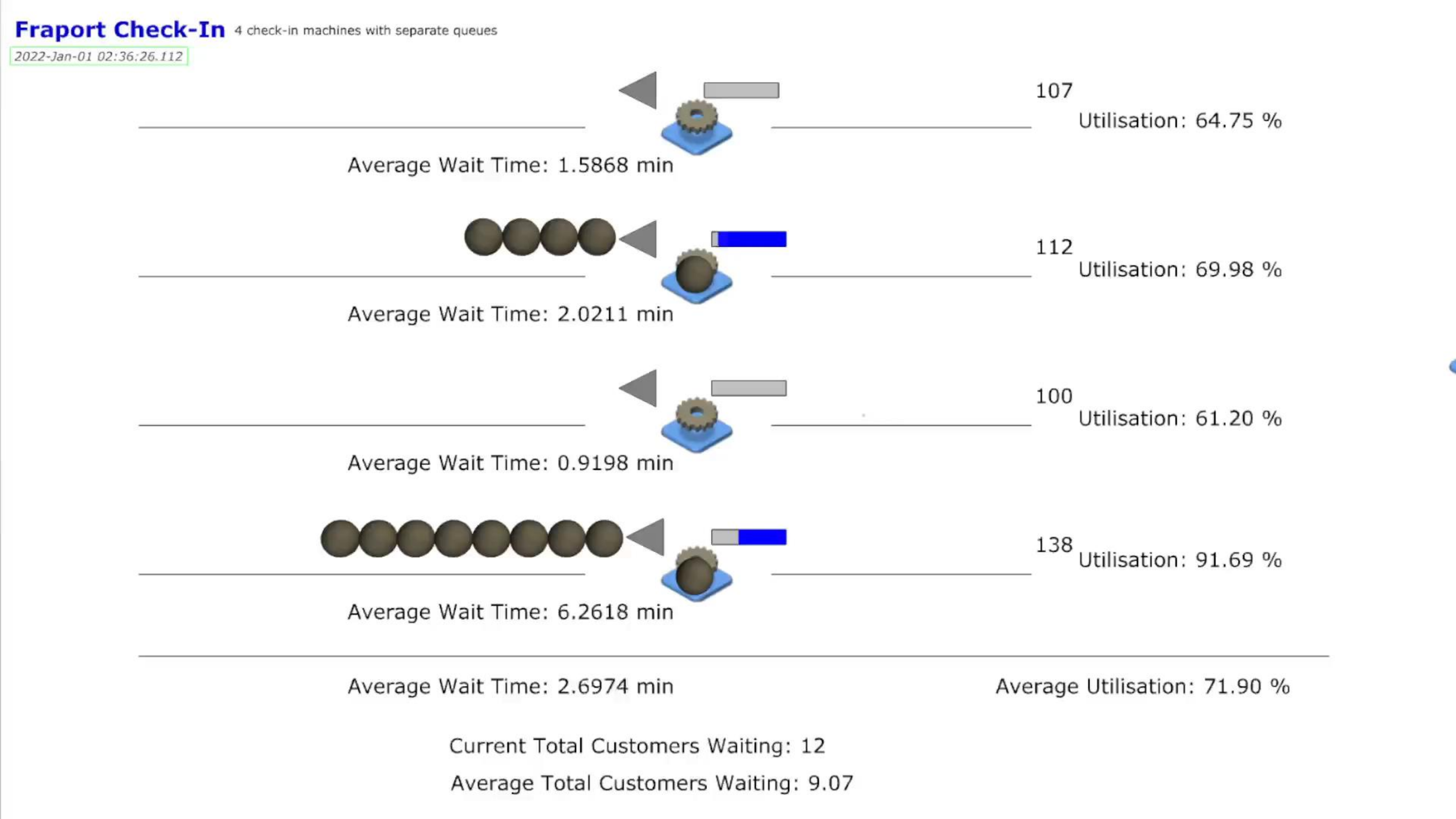




https://www.fraport.de/

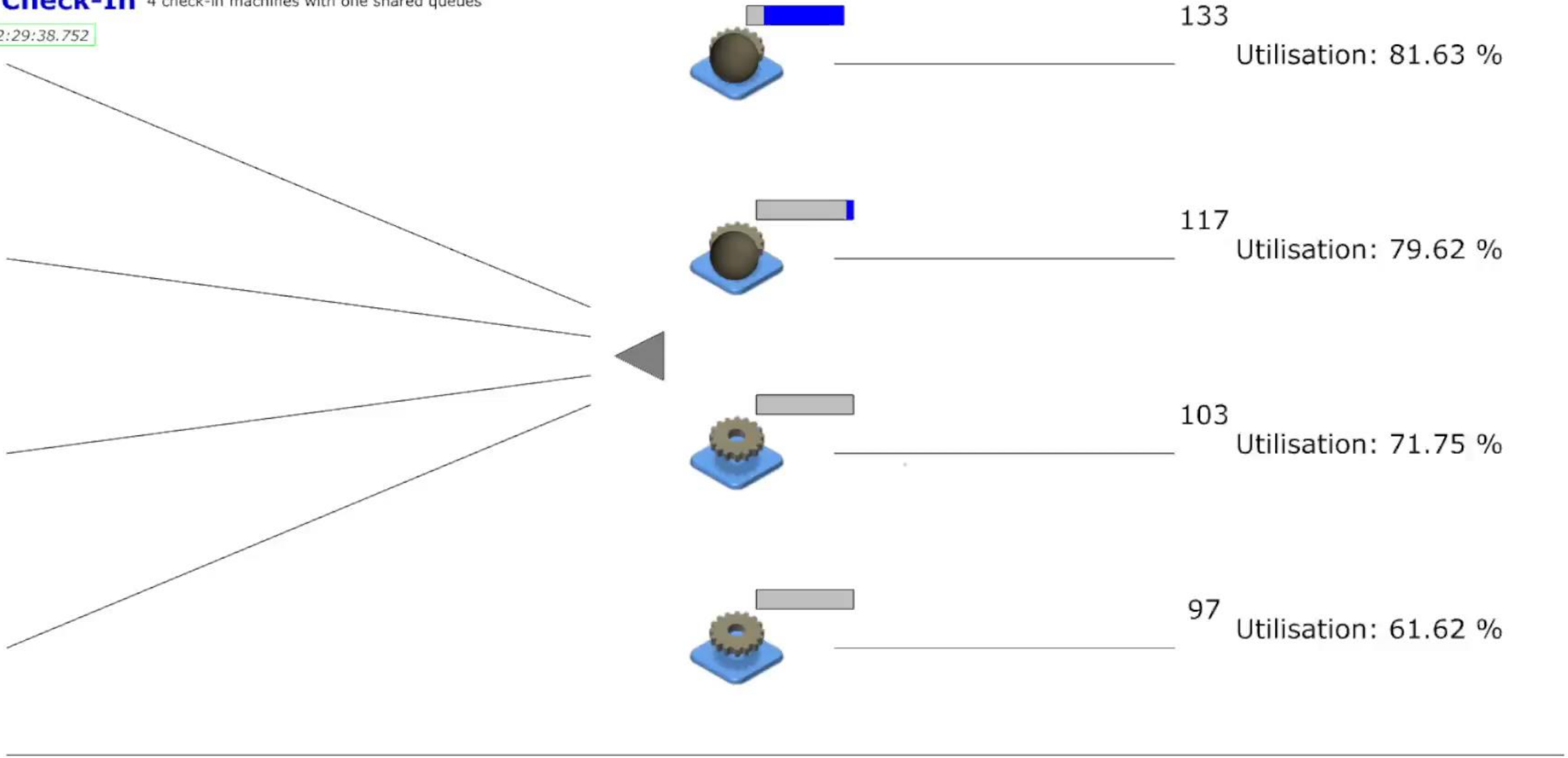
# Comparison

| | Dedicated queue system | Pooled queue system |
|---|---|---|
| |  |  |
| Utilization | 75 % | 75 % |
| Waiting time per passenger | 3 min | 0.5368 min |
| Number of passengers waiting in line(s) | $4 \cdot 2.25 =$ 9 passengers | 1.6105 passengers |


Fraport Check-In
4 check-in machines with separate queues
2022-Jan-01 02:36:26.112
107
Utilisation: 64.75 %
Average Wait Time: 1.5868 min
112
Utilisation: 69.98 %
Average Wait Time: 2.0211 min
100
Utilisation: 61.20 %
Average Wait Time: 0.9198 min
138
Utilisation: 91.69 %
Average Wait Time: 6.2618 min
Average Wait Time: 2.6974 min
Average Utilisation: 71.90 %
Current Total Customers Waiting: 12
Average Total Customers Waiting: 9.07

**Fraport Check-In** 4 check-in machines with one shared queues

2022-Jan-01 02:29:38.752




Average Wait Time: 0.3460 min

Average Utilisation: 73.65 %

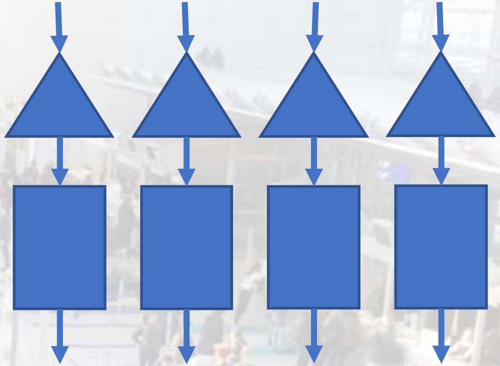
Current Total Customers Waiting: 0

Average Total Customers Waiting: 1.05

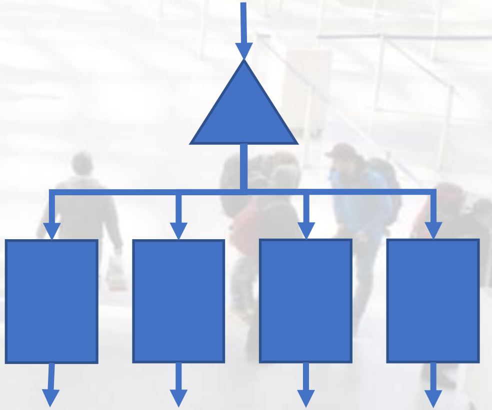
# The Power of Pooling

- Servers do neither work more nor work faster. Utilization is the same.
- Pooled process uses available capacity more effectively.
- Pooling prevents the case that one resource is idle (e.g., no passengers at check-in machine 1) while the other faces a backlog of work (e.g., multiple passengers in queue at machine 2).
- Pooling identical resources balances the load for the servers, leading to shorter waiting times.

Dedicated queue system



Pooled queue system



# Limitations to Pooling

- Pooling may require workers to have a broader set of skills, which may require more training and higher wages.

- Pooling may disrupt the customer – server relationship.

- Pooling may increase the time-in-queue for one customer class at the expense of another.

- Pooling may require investment and lead to higher fixed costs.

# SYSTEM SIZE AND ECONOMIES OF SCALE

# Fraport Terminal 2 Challenges

- What is the minimum number of machines that must be installed?
- How does the size of machine pools affect the waiting time?




https://www.fraport.de/

# What is the Minimum Number of Machines?

$$\begin{matrix} Minimum \\ number \\ of\ servers \end{matrix} > \frac{p}{a}$$

- p is exponentially distributed with a mean of 1 minute
- a is exponentially distributed with a mean of 1/3 minutes
- If less than the minimum number of machines are available, number of passengers in the system could explode:



https://www.fraport.de/

# Fraport Terminal 2 Challenges

- What is the minimum number of machines that must be installed?
- How does the size of machine pools affect the waiting time?

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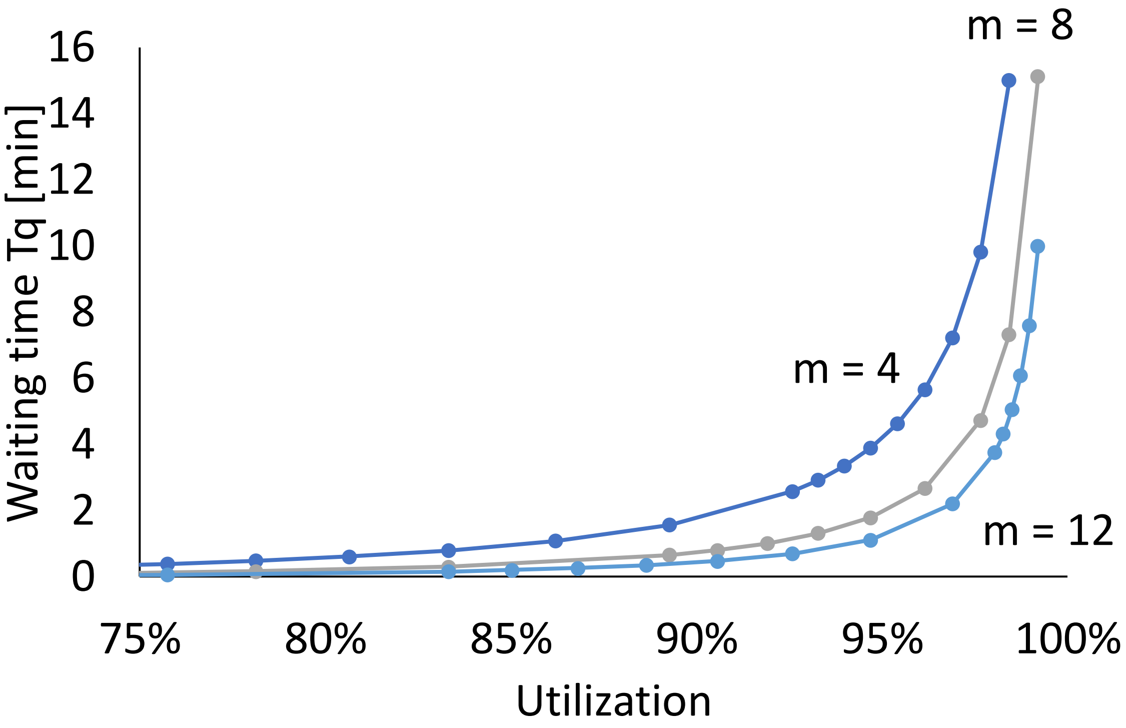
# Economies of Scale




The same applies:

The waiting time for customers increases progressively with the capacity utilisation of the check-in machines.

But:

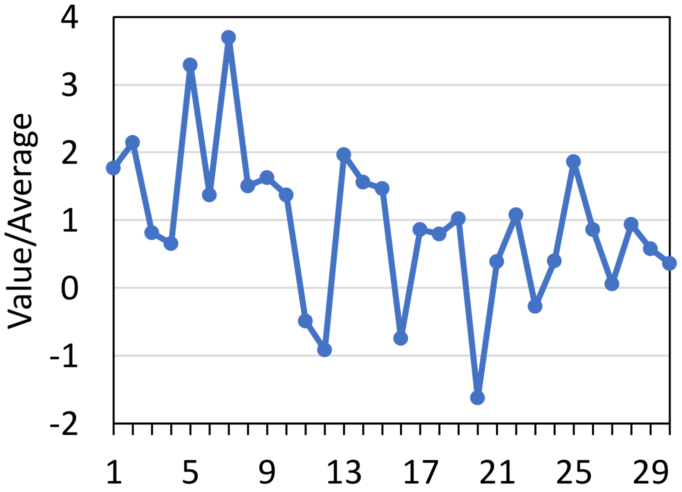
The larger the pool of machines, the later the increase occurs and the less sensitive the waiting time reacts to an increase in occupancy.

# EXTRA

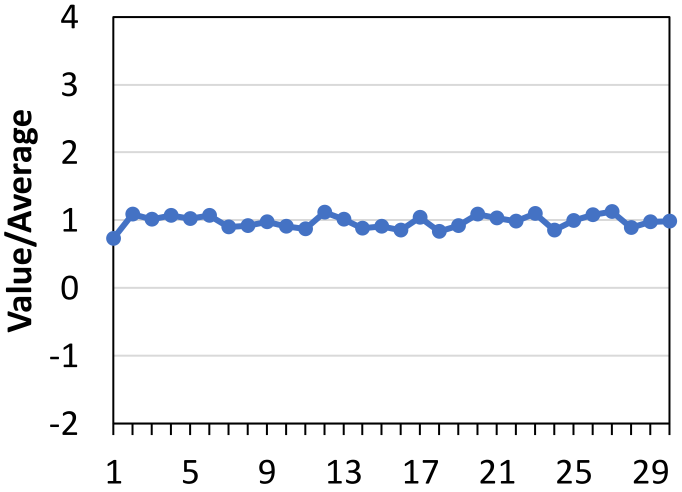
# Coefficient of Variation – A Measure of Variability

$$Coefficient\ of\ Variation\ CV = \frac{Standard\ Deviation}{Mean}$$

$$CV = \frac{10}{10} = 1$$




$$CV = \frac{10}{100} = 0.1$$

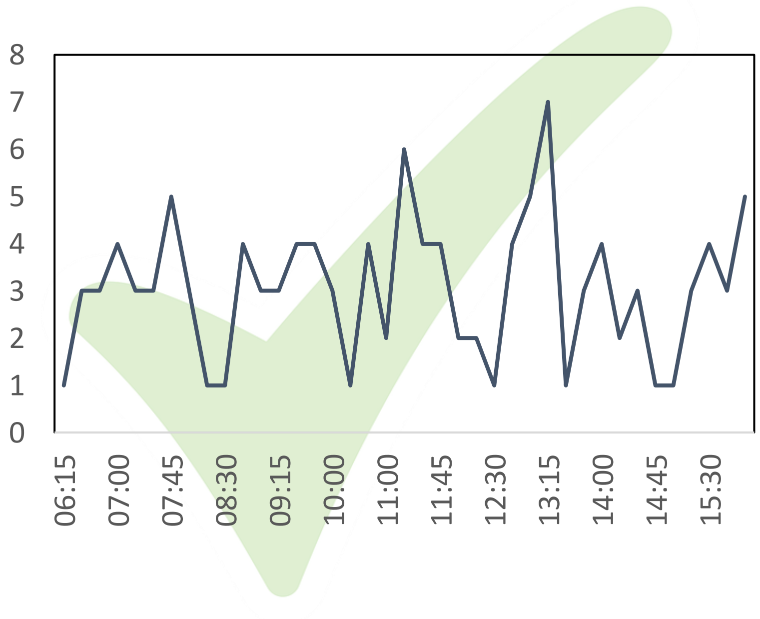


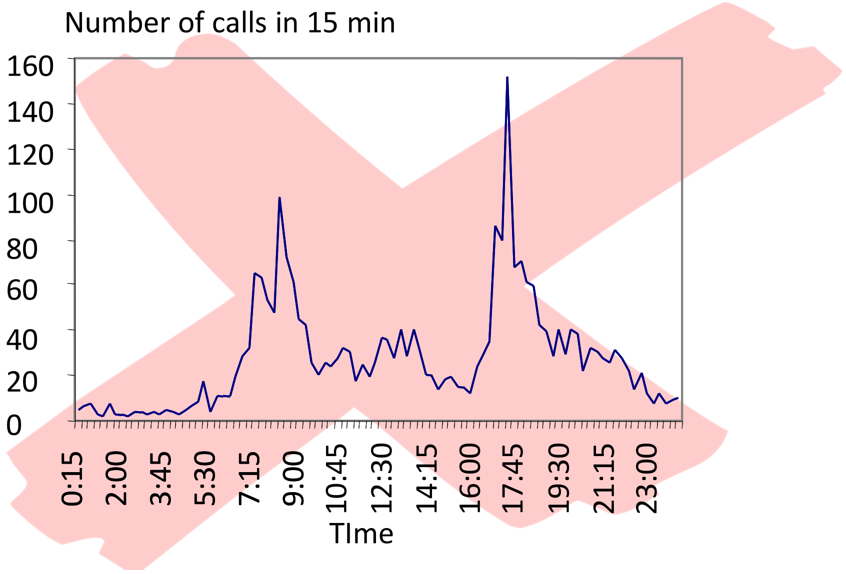
E2



# Prerequisites for the waiting time formula

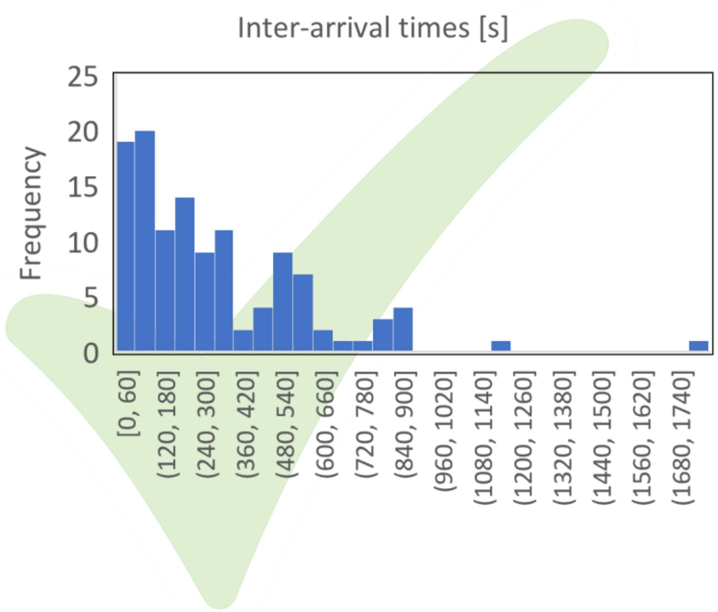
1. Constant average arrival rates

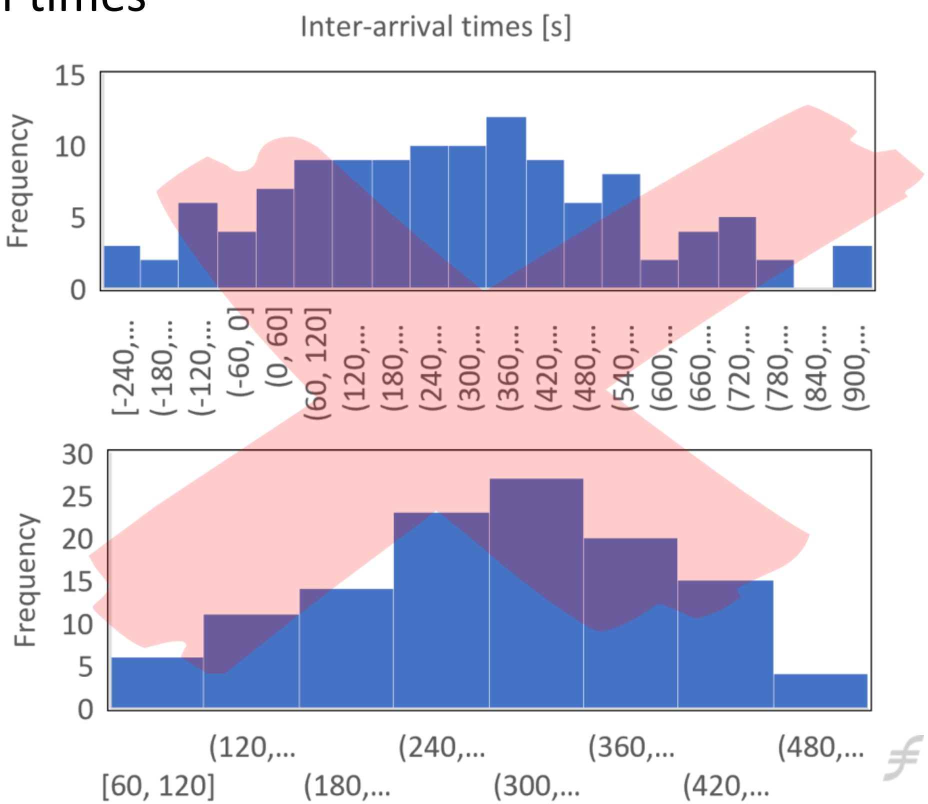


# Prerequisites for the waiting time formula

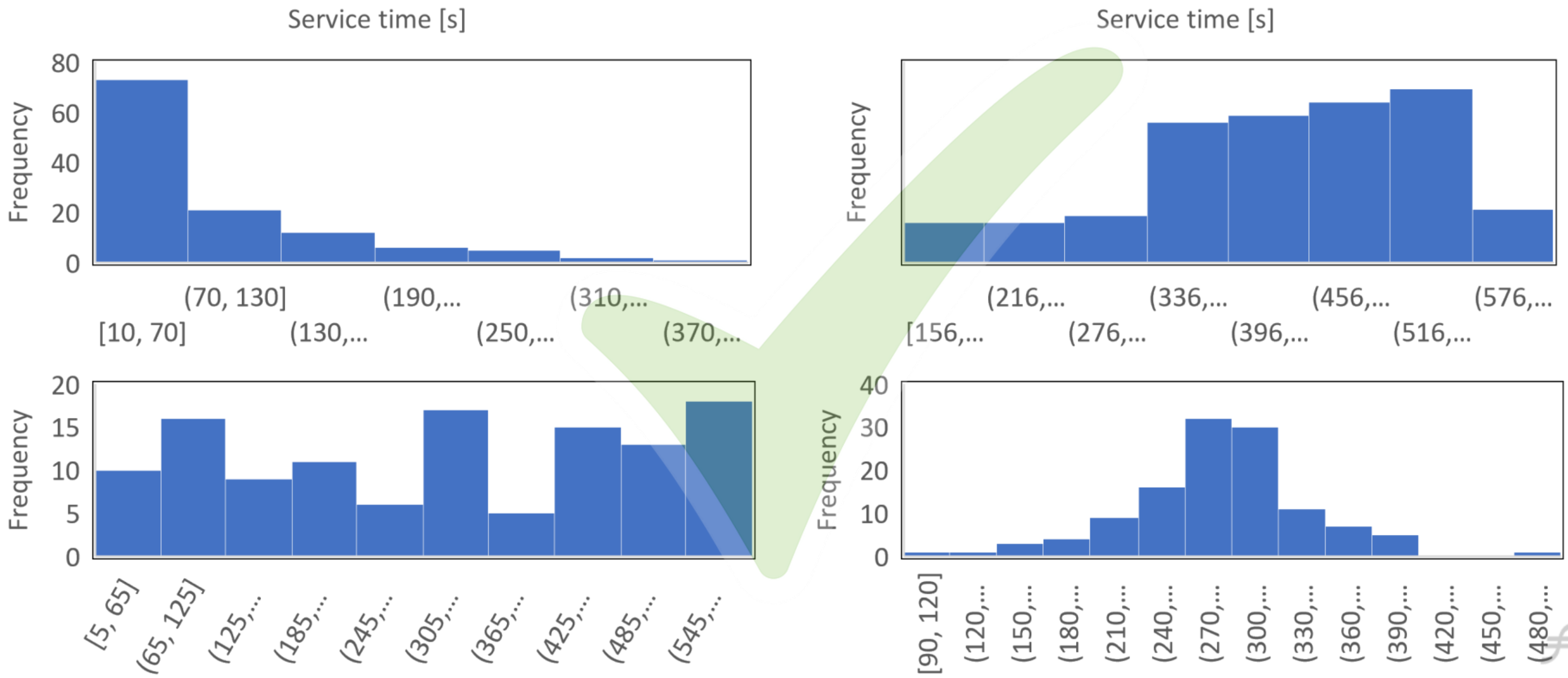
2. Exponentially distributed inter-arrival times



# Prerequisites for the waiting time formula

3. Arbitrarily distributed operating/service times



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Frankfurt School

# 2023
# Operations Management

# SERVICE SYSTEMS WITH IMPATIENT CUSTOMERS

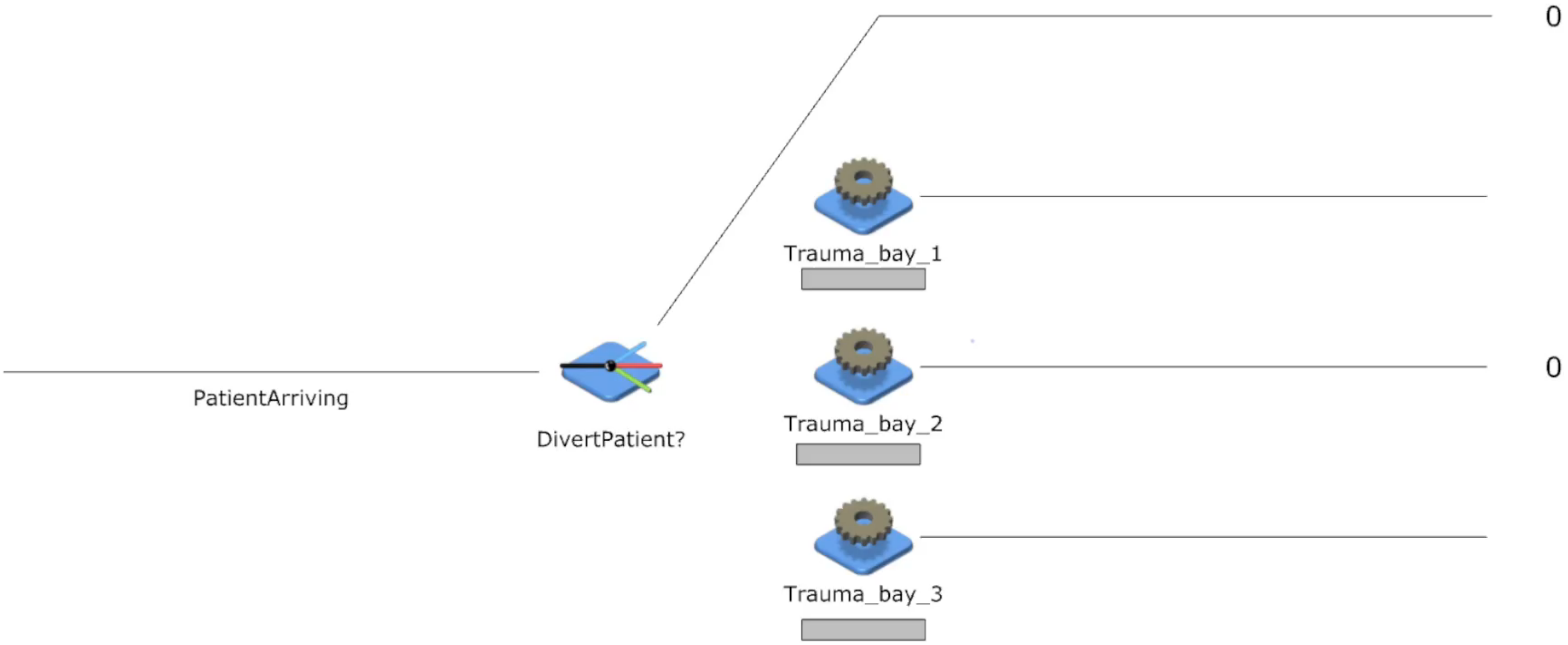
# LOST DEMAND IN QUEUES WITH NO BUFFERS

# Trauma Center

- Hospital equipped and staffed to provide care for patients suffering from major traumatic injuries such as falls, motor vehicle collisions, or gunshot wounds
- Full range of specialists and equipment available 24 hours a day[
- Operation of a trauma center is extremely expensive

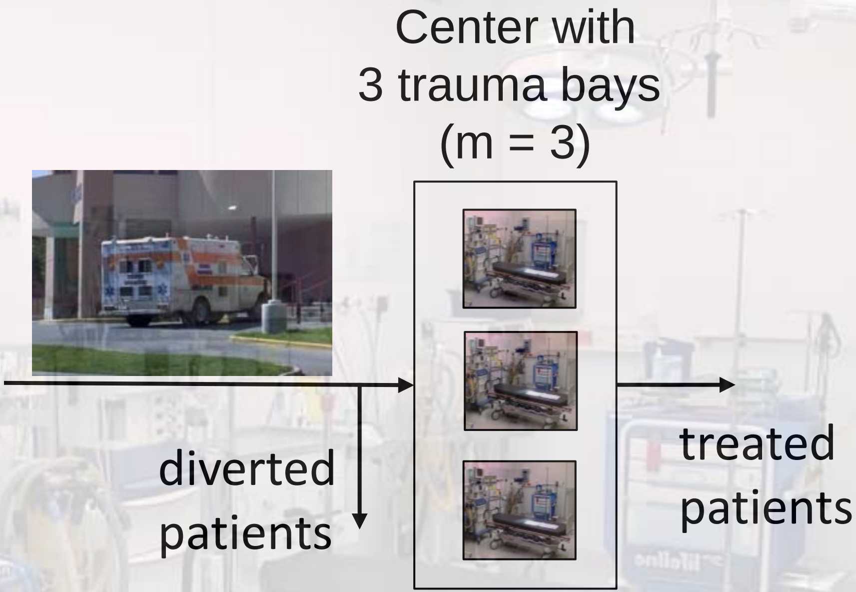
## Trauma Center

*01-Jan-2022 08:00:00*



# Trauma Center Challenge

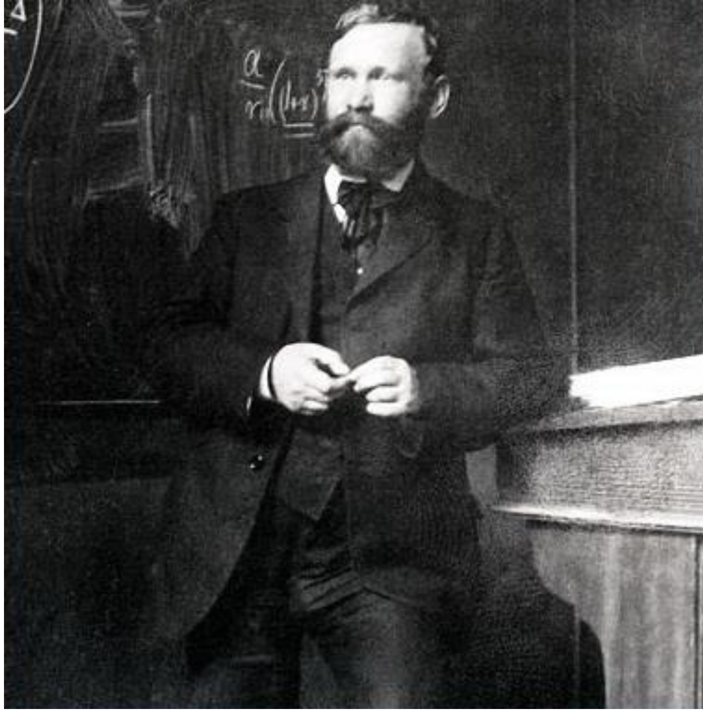
- What is the probability that all trauma bays are utilized?
- How many trauma patients need to be diverted?
- What is the utilization of the trauma bays?
- How many trauma bays are needed to guarantee a diversion probability of less than 1%?




- Demand:
  One trauma case comes in every 3 hours.
- Processing:
  Patient stays in trauma bay for an average of 2 hours.

# The Erlang Loss Model

- There are m servers.
- Customers are processed by a single server.
- The average interarrival time is a. The coefficient of variation $CV_a$ is 1. (Interarrival times are exponentially distributed.)
- The average processing time is p for any distribution..
- Customers do not wait. At most m customers are in the system.



Agner Krarup Erlang (1878 –1929) was a Danish mathematician, statistician and engineer, who invented the fields of traffic engineering and queueing theory.

# Capacity and Implied Utilization

$Capacity$

$Demand\ rate$

$Implied\ utilization$

- Resources:
  Center with 3 trauma bays.
- Demand:
  One trauma case comes in every 3 hours.
- Processing:
  Patient stays in trauma bay for an average of 2 hours.

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

$$Implied\ utilization = \frac{Demand\ rate}{Capacity}$$

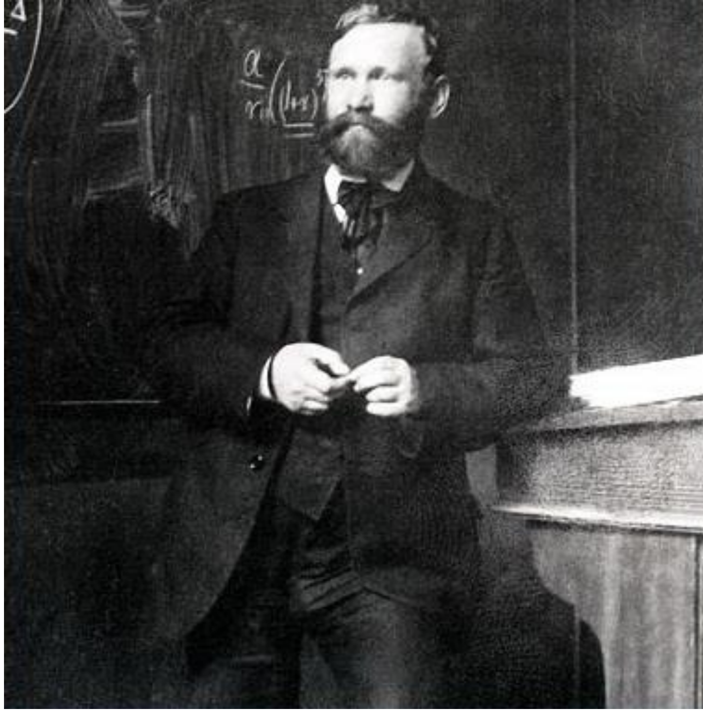
# The Erlang Loss Formula

The probability that all servers are busy is given by the following „nasty“ formula:

$$P_m(r) = \frac{\frac{r^m}{m!}}{1 + \frac{r^1}{1!} + \frac{r^2}{2!} + \ldots + \frac{r^m}{m!}}$$

r is the so-called **offered load** – a measure of how much demand is loaded on the system relative to the capacity of one server:

$$r = \frac{p}{a}$$



Agner Krarup Erlang (1878 –1929) was a Danish mathematician, statistician and engineer, who invented the fields of traffic engineering and queueing theory.

# Using the Erlang Loss Table

Offered load:

$$r = \frac{p}{a} =$$

$$P_m(r) = P \quad ( \quad ) =$$

**Erlang Loss Table**

| | m | | | | | | |
|---|---|---|---|---|---|---|---|
| r = p/a | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 0.10 | 0.0909 | 0.0045 | 0.0002 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 0.20 | 0.1667 | 0.0164 | 0.0011 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |
| 0.25 | 0.2000 | 0.0244 | 0.0020 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |
| 0.30 | 0.2308 | 0.0335 | 0.0033 | 0.0003 | 0.0000 | 0.0000 | 0.0000 |
| 0.33 | 0.2481 | 0.0393 | 0.0043 | 0.0004 | 0.0000 | 0.0000 | 0.0000 |
| 0.40 | 0.2857 | 0.0541 | 0.0072 | 0.0007 | 0.0001 | 0.0000 | 0.0000 |
| 0.50 | 0.3333 | 0.0769 | 0.0127 | 0.0016 | 0.0002 | 0.0000 | 0.0000 |
| 0.60 | 0.3750 | 0.1011 | 0.0198 | 0.0030 | 0.0004 | 0.0000 | 0.0000 |
| 0.67 | 0.4012 | 0.1185 | 0.0258 | 0.0043 | 0.0006 | 0.0001 | 0.0000 |
| 0.70 | 0.4118 | 0.1260 | 0.0286 | 0.0050 | 0.0007 | 0.0001 | 0.0000 |
| 0.75 | 0.4286 | 0.1385 | 0.0335 | 0.0062 | 0.0009 | 0.0001 | 0.0000 |

# Offered Load vs Implied Utilization

- In common:
  both measures give a sense of the amount of demand relative to the capacity of the system
- In contrast:
  - Offered load **does not** account for the number of servers in a system
  - Implied utilization does consider the actual number of servers

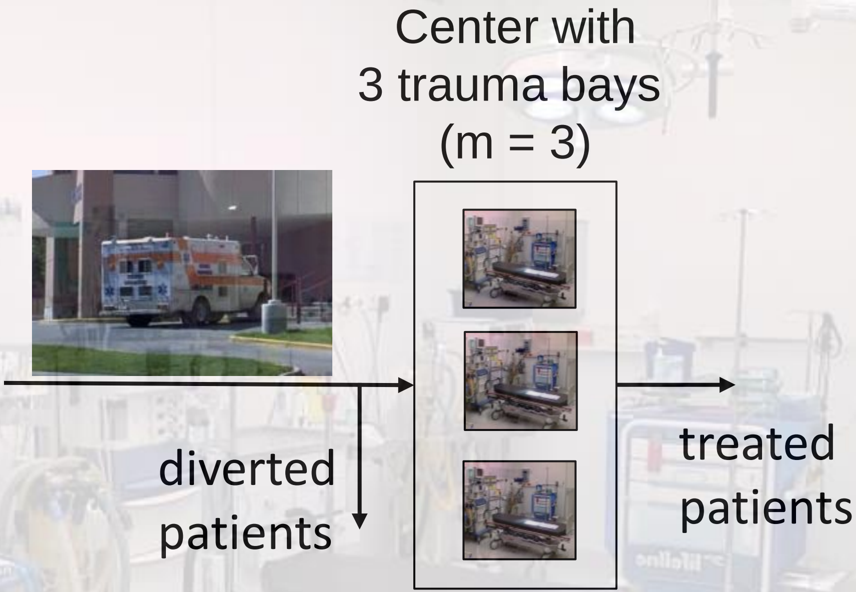
$$r = u \cdot m = \frac{2}{9} \cdot 3 = \frac{2}{3}$$

$$r = \frac{p}{a} = \frac{2h}{3h} = \frac{2}{3}$$

$$Implied\,utilization = \frac{Demand\ rate}{Capacity} = \frac{\frac{1}{a}}{\frac{m}{p}} = \frac{p}{m \cdot a} = \frac{2}{3 \cdot 3}$$

# Trauma Center Challenge

- What is the probability that all trauma bays are utilized?
- **How many trauma patients need to be diverted?**
- What is the utilization of the trauma bays?
- How many trauma bays are needed to guarantee a diversion probability of less than 1%?

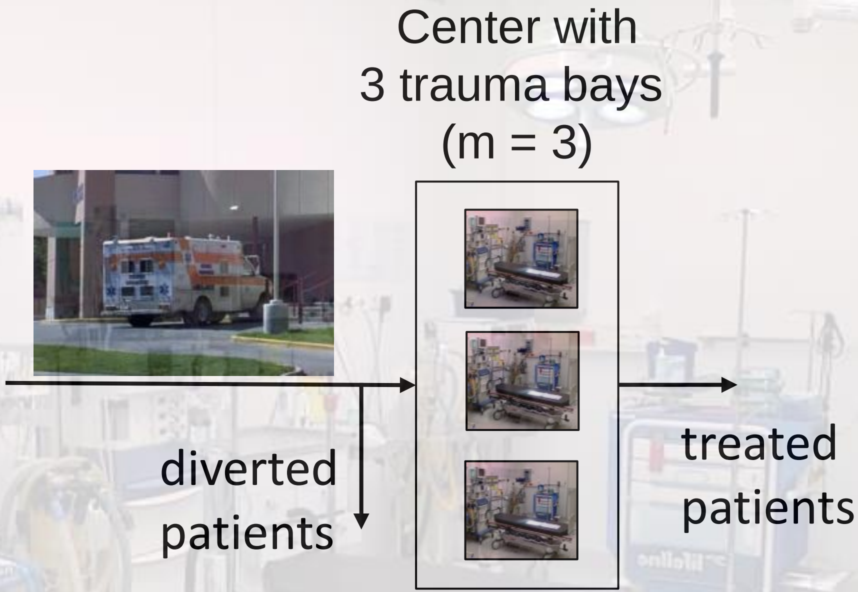



- Demand:
  One trauma case comes in every 3 hours.
- Processing:
  Patient stays in trauma bay for an average of 2 hours.

# Rate of Diverted Patients

$$\begin{gathered}Rate\ of\\ lost\ demand\end{gathered}$$

$$Flow\ rate$$

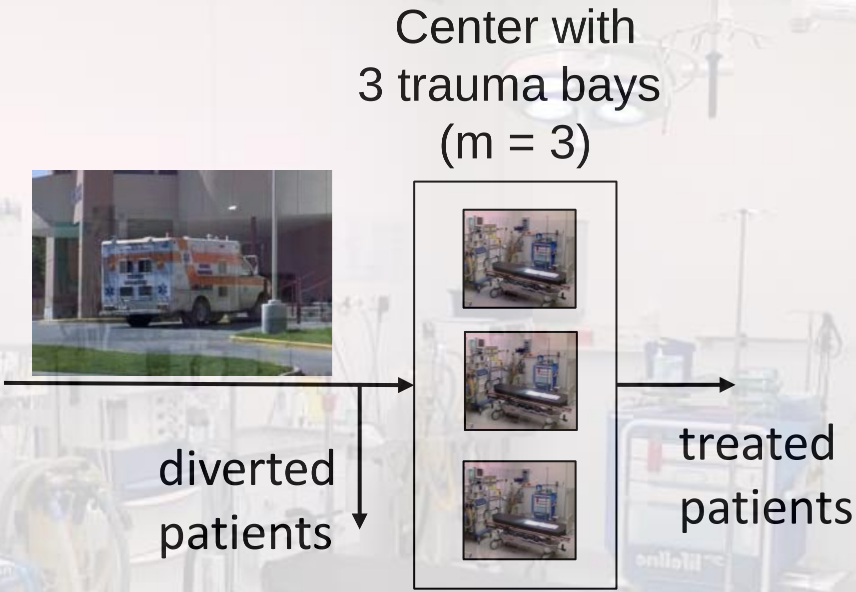



$$Flow\ rate = \frac{1}{a} \cdot (1 - P_m)$$

$$\begin{gathered}Rate\ of\\ lost\ demand\end{gathered} = \frac{1}{a} \cdot P_m$$

# Trauma Center Challenge

- What is the probability that all trauma bays are utilized?
- How many trauma patients need to be diverted?
- **What is the utilization of the trauma bays?**
- How many trauma bays are needed to guarantee a diversion probability of less than 1%?

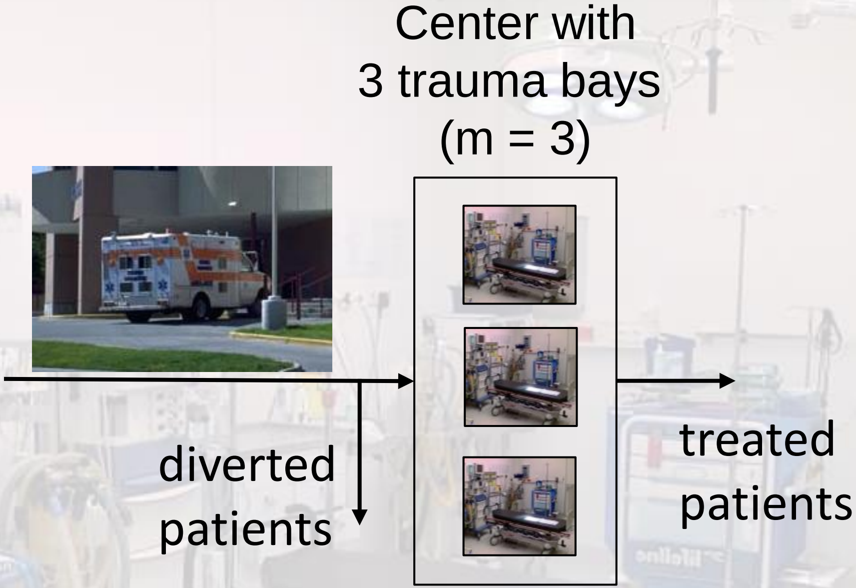



- Demand:
  One trauma case comes in every 3 hours.
- Processing:
  Patient stays in trauma bay for an average of 2 hours.

# Utilization of the Trauma Bays

$Utilization$

$Average\ number\ of\ occupied\ servers$

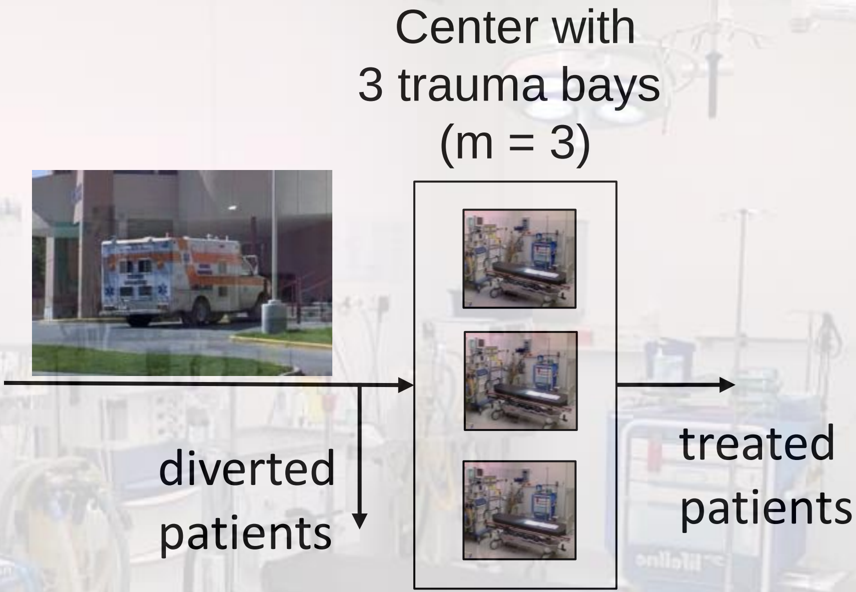



$$Utilization = \frac{Flow\ rate}{Capacity}$$

$$= \frac{Processing\ time}{m} \cdot Flow\ rate$$

# Trauma Center Challenge

- What is the probability that all trauma bays are utilized?
- How many trauma patients need to be diverted?
- What is the utilization of the trauma bays?
- **How many trauma bays are needed to guarantee a diversion probability of less than 1%?**




- Demand:
  One trauma case comes in every 3 hours.
- Processing:
  Patient stays in trauma bay for an average of 2 hours.

# Trauma Bays Needed

We begin with the offered load:

$$r = \frac{p}{a} = \frac{2h}{3h} = \frac{2}{3}$$

**Erlang Loss Table**

| | m | | | | | | |
|---|---|---|---|---|---|---|---|
| r = p/a | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 0.10 | 0.0909 | 0.0045 | 0.0002 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
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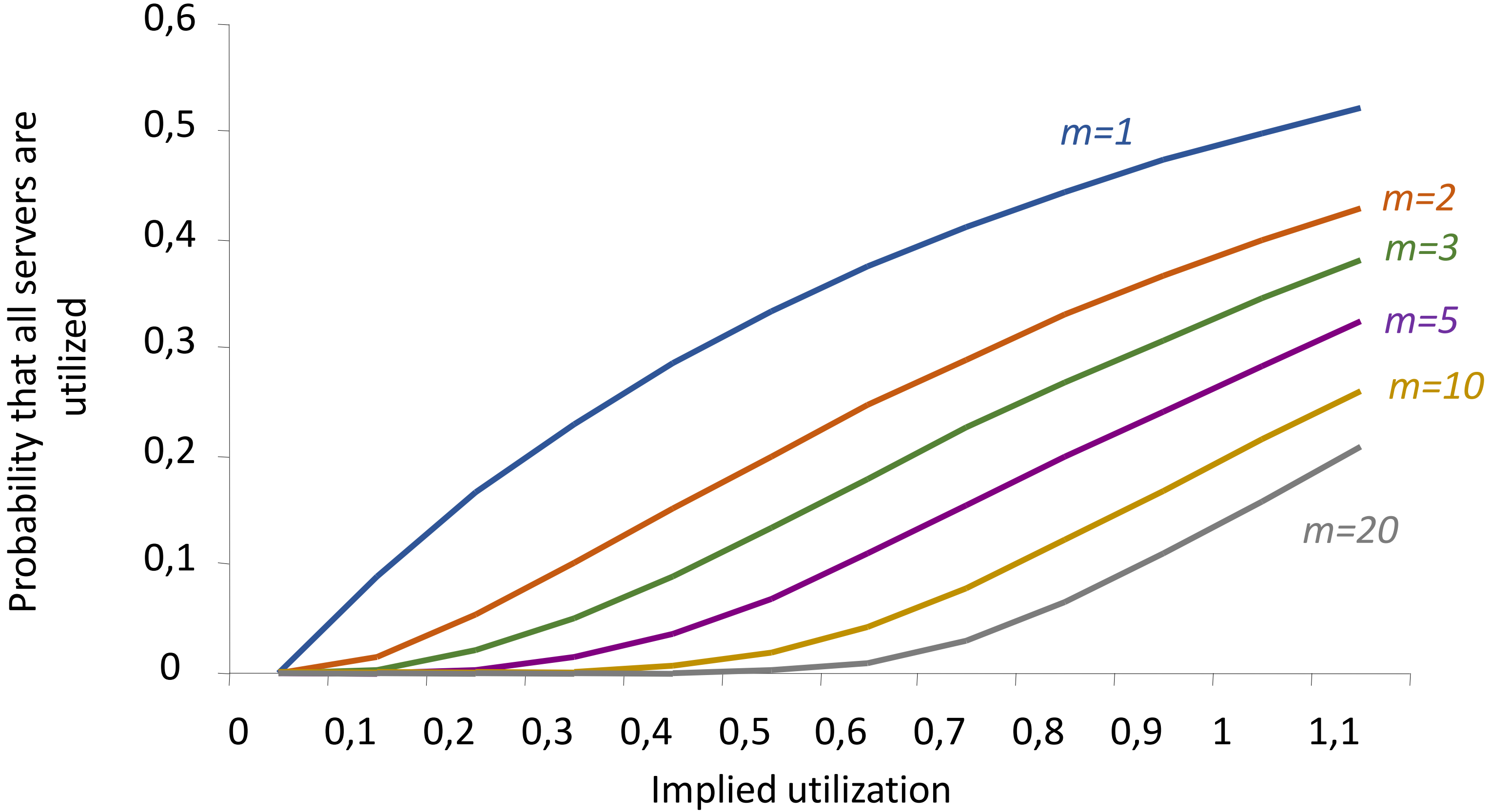
| 0.50 | 0.3333 | 0.0769 | 0.0127 | 0.0016 | 0.0002 | 0.0000 | 0.0000 |
| 0.60 | 0.3750 | 0.1011 | 0.0198 | 0.0030 | 0.0004 | 0.0000 | 0.0000 |
| 0.67 | 0.4012 | 0.1185 | 0.0258 | 0.0043 | 0.0006 | 0.0001 | 0.0000 |
| 0.70 | 0.4118 | 0.1260 | 0.0286 | 0.0050 | 0.0007 | 0.0001 | 0.0000 |
| 0.75 | 0.4286 | 0.1385 | 0.0335 | 0.0062 | 0.0009 | 0.0001 | 0.0000 |

# MANAGING A QUEUE WITH IMPATIENT CUSTOMERS

# Economies of Scale



# A Second Perspective on Economies of Scale

| Offered Load, r | Number of Servers, m | $P_m$ | Implied Utilization | Utilization |
|---|---|---|---|---|
| 1 | 4 | 0.015 | 25% | 25% |
| 5 | 10 | 0.018 | 50% | 49% |
| 10 | 17 | 0.013 | 59% | 58% |
| 25 | 34 | 0.016 | 74% | 72% |
| 50 | 61 | 0.017 | 82% | 81% |
| 100 | 113 | 0.018 | 88% | 87% |

Number of servers required for different offered loads to achieve a probability that all servers are busy that is no more than 0.02

# Pooling of Erlang Loss Systems

| | A | B | A+B = C |
|---|---|---|---|
| a | 0.20 | 0.20 | 0.10 |
| p | 0.15 | 0.15 | 0.15 |
| m | 2 | 2 | 4 |
| Demand rate = 1/a | 5 | 5 | 10 |
| Capacity = m/p | 13.33 | 13.33 | 26.67 |
| Implied utilization = p/(a x m ) | 37.5% | 37.5% | 37.5% |
| Offered load, r = p/a | 0.75 | 0.75 | 1.5 |
| $P_m$ | 0.1385 | 0.1385 | 0.048 |
| Flow rate = (1- $P_m$)/a | 4.31 | 4.31 | 9.52 |
| Utilization = Flow rate/Capacity | 32% | 32% | 36% |

The performance of two separate Erlang loss systems, A and B, compared to the performance of the pooled system that combines the two together

# The Performance of Different Levels of Pooling

| | Number of Independent Systems | | | | |
|---|---|---|---|---|---|
| | 16 | 8 | 4 | 2 | 1 |
| a | 0.2000 | 0.1000 | 0.0500 | 0.0250 | 0.0125 |
| p | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| m | 2 | 4 | 8 | 16 | 32 |
| Demand rate = 1/a | 5 | 10 | 20 | 40 | 80 |
| Capacity = m/p | 13.33 | 26.67 | 53.33 | 106.67 | 213.33 |
| Implied utilization = p/(a x m ) | 37.5% | 37.5% | 37.5% | 37.5% | 37.5% |
| Offered load, r = p/a | 0.75 | 1.5 | 3 | 6 | 12 |
| $P_m$ | 0.1385 | 0.048 | 0.0081 | 0.0003 | 0.0000 |
| Flow rate = $(1- P_m)/a$ | 4.31 | 9.52 | 19.84 | 39.99 | 80.0 |
| Utilization = Flow rate/Capacity | 32.3% | 35.7% | 37.2% | 37.5% | 37.5% |

Note: The column header is the number of independent systems. For example, the first column has 16 independent systems, while the second column describes pooling pairs of systems to create 8 independent systems. In the last column there is only one system with then 32 resources.

# Trauma Center with 2 Buffers

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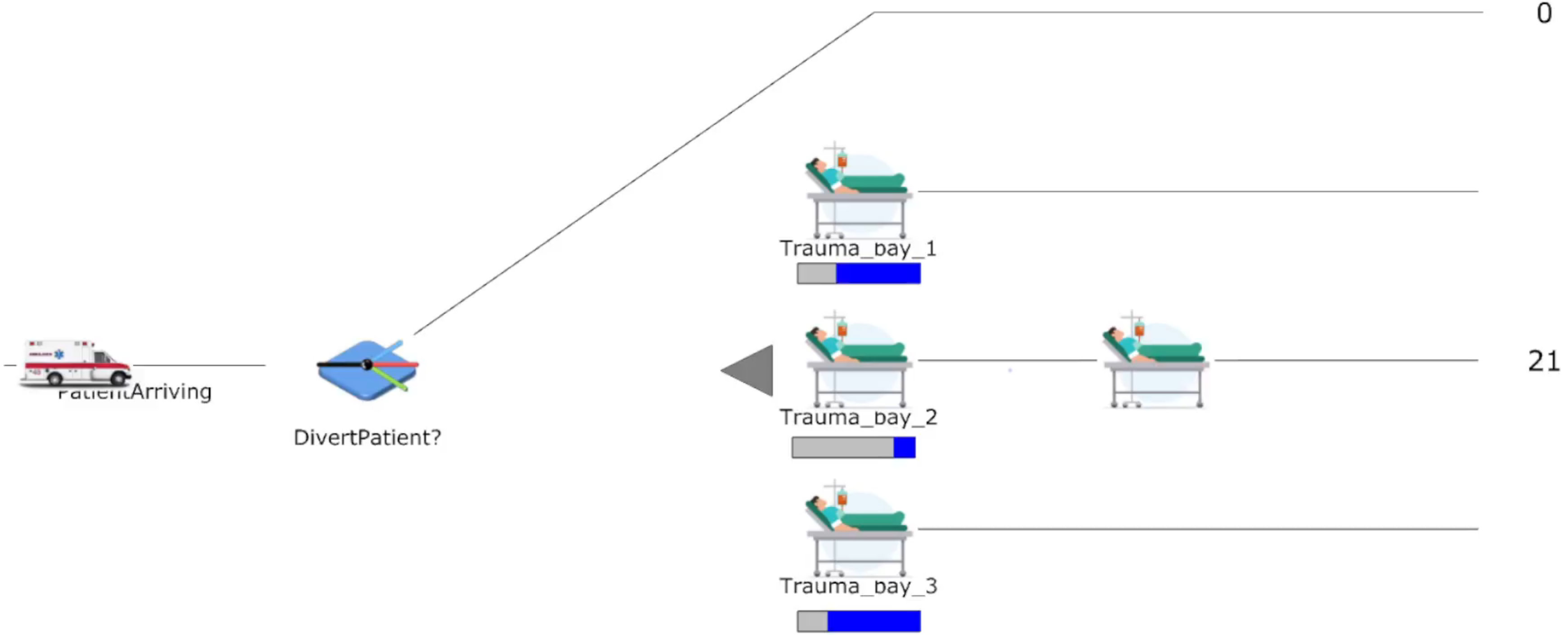
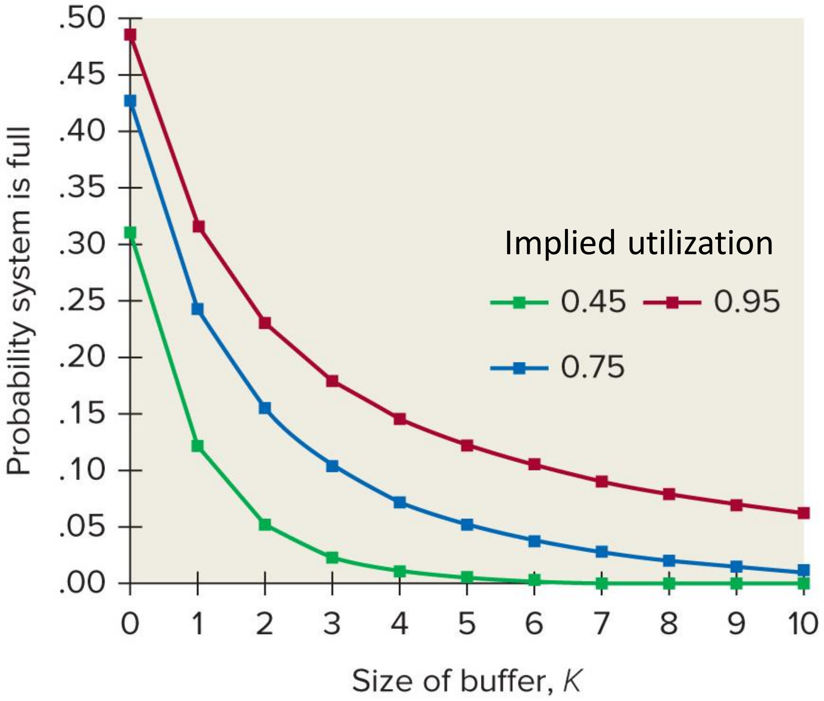
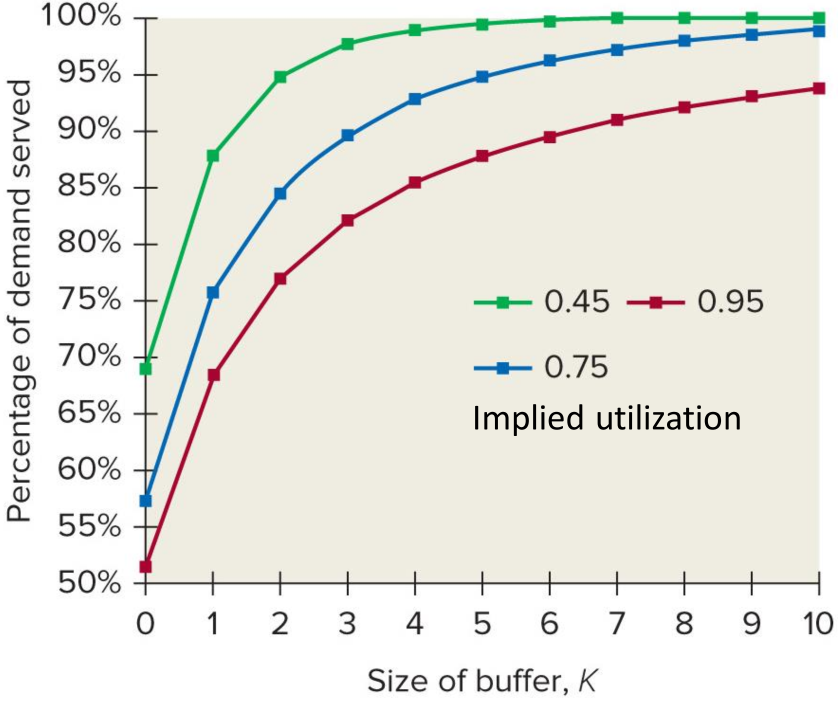


# Impact of Increasing the Buffer Size

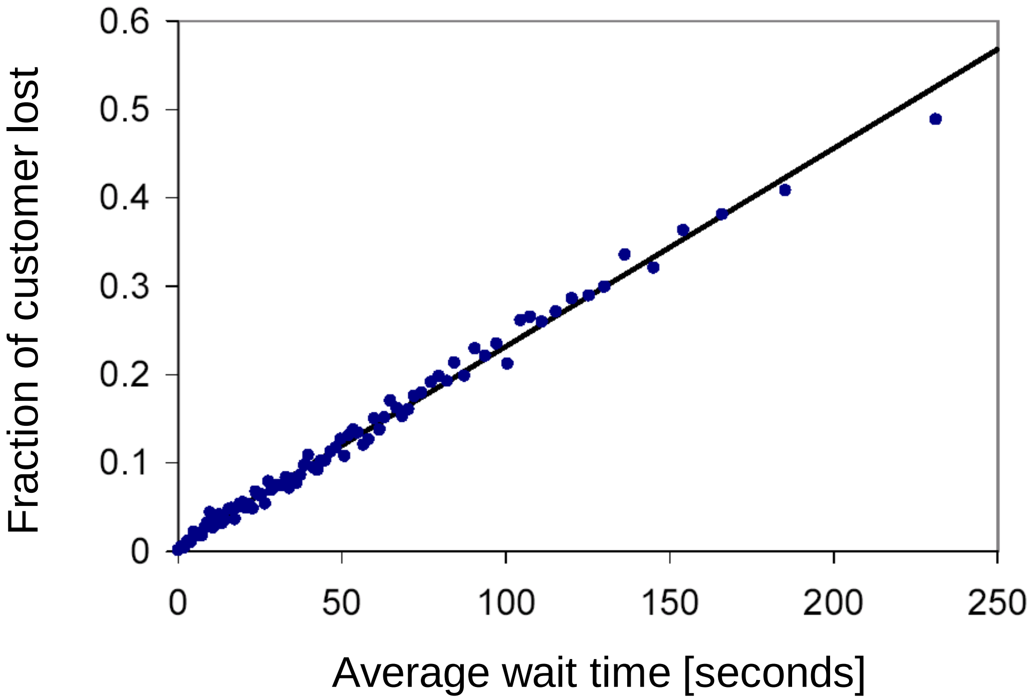


# Issues with Buffers

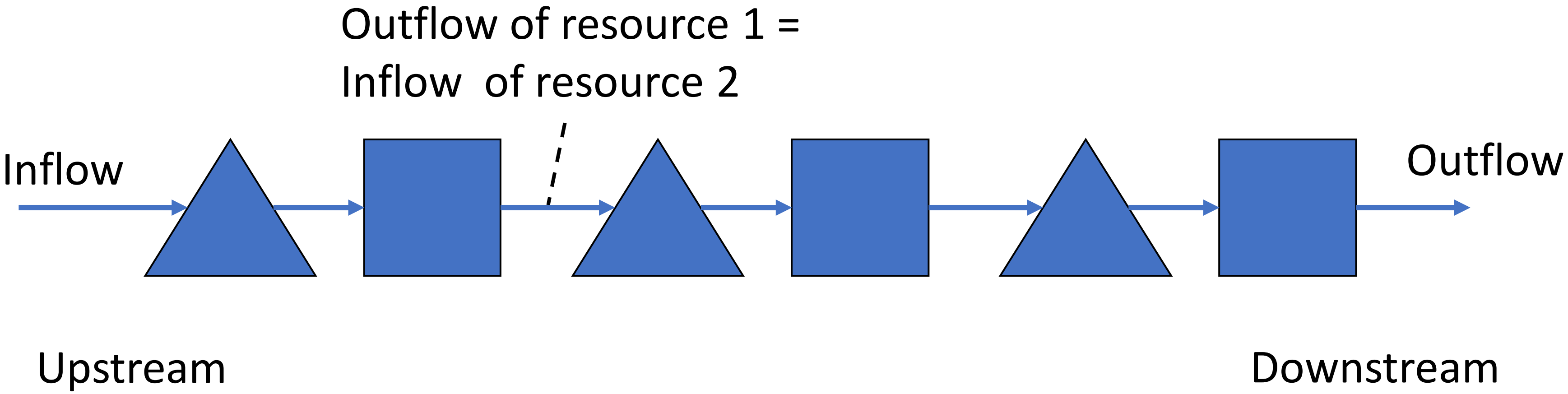
- Some customers might not be able to wait
- Balking: Customers choose not to join a queue
- Reneging/abandoning: Customers choose to leave the queue after joining it

# Impact of Waiting Time on Customer Loss

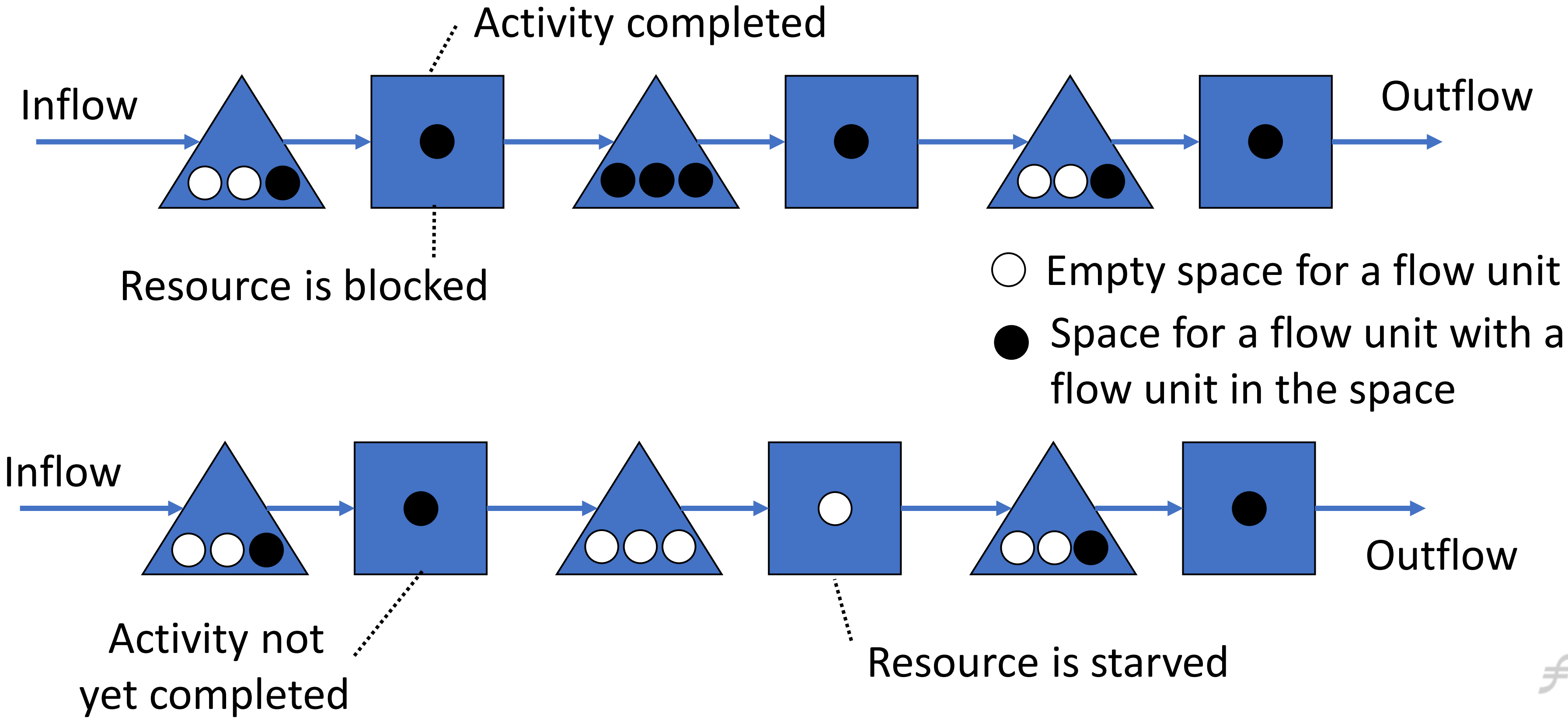



Source: Gans, Koole, and Mandelbaum, 2003

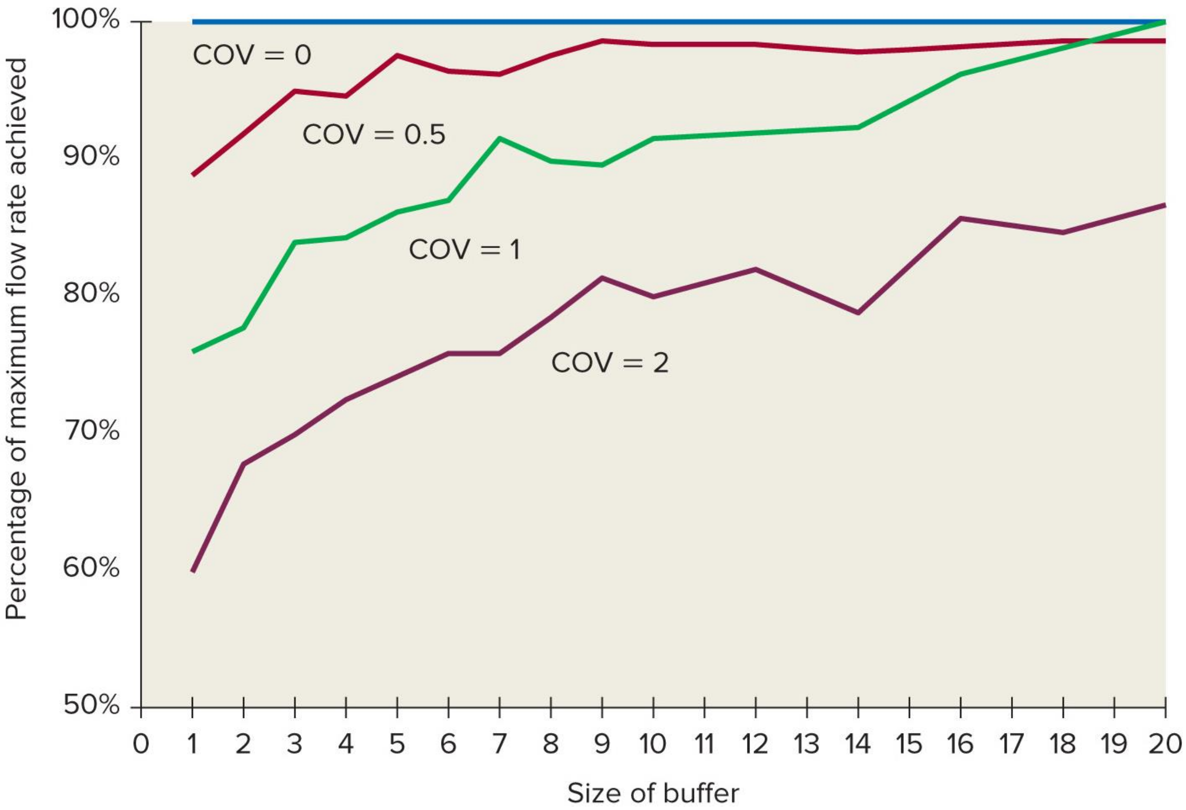
# A Process with Sequential Resources

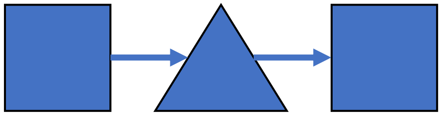


# The Concepts of Blocking and Starving



# Impact of Variability on a Tandem Process



The flow rate of a two-resource tandem queue as a percentage of the flow rate without any variability. Different levels of variability in processing times (COV) are displayed on different lines. The coefficient of variation of the arrival process is always 1.

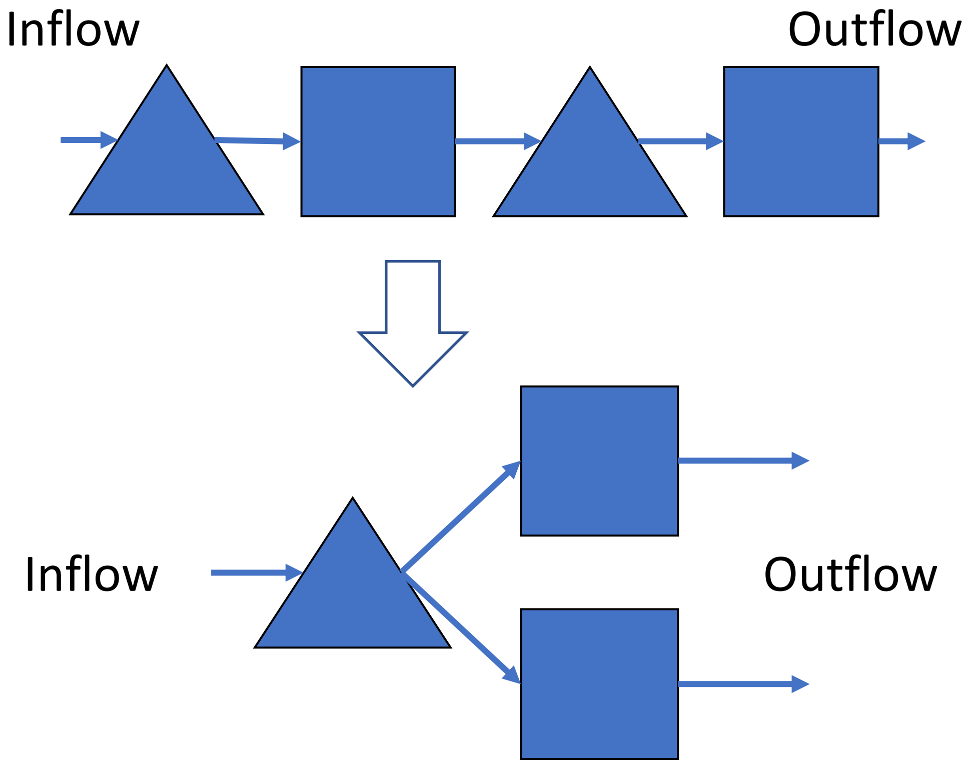
# Buffer or Suffer

For a special process with applied resources:

- The greater the variability at constant buffer stock size, the lower the capacity.
- The larger the size of the buffer stock at constant variability, the higher the capacity.

But be aware of the disadvantages of buffers!

# Parallel instead of Sequential Production Designs




But – parallelisation also has disadvantages

# Reduce Variability in Processing Times

Standard working procedures

- Task/movement analysis
- Development of best practice
- Documentation of guidelines and instructions how a task is to be completed
- Continuous monitoring and updating

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EFMD EQUIS ACCREDITED
ASSOCIATION OF MBAS ACCREDITED

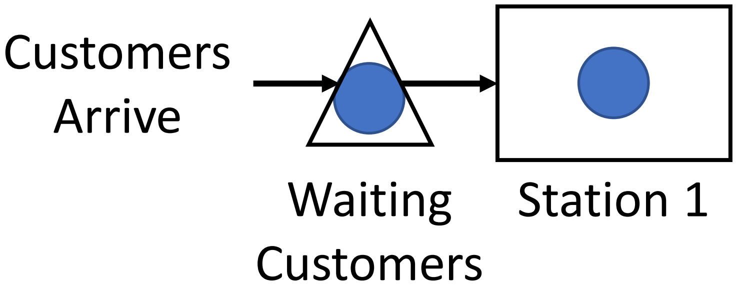

# 2023
# Operations Management

# INTRODUCTION TO INVENTORY MANAGEMENT

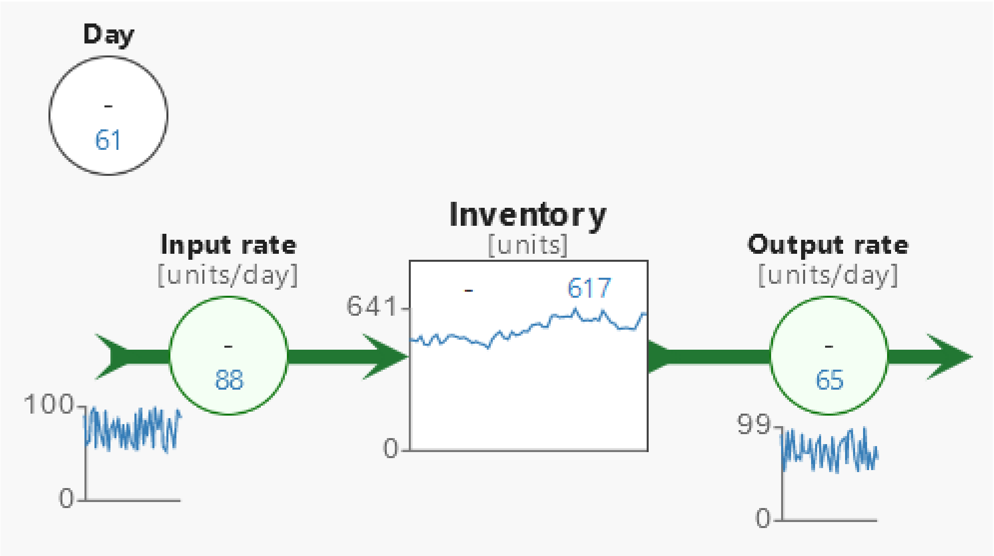
# INVENTORY MANAGEMENT

# Graphical Symbols for Inventory

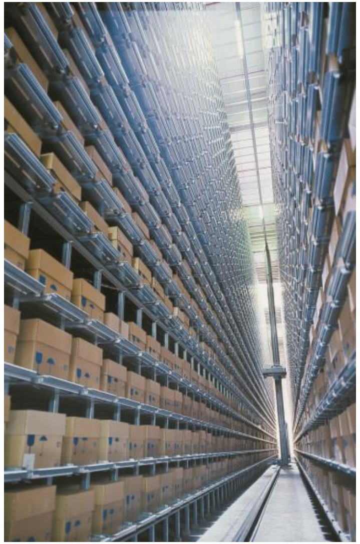
Process Flow Diagram

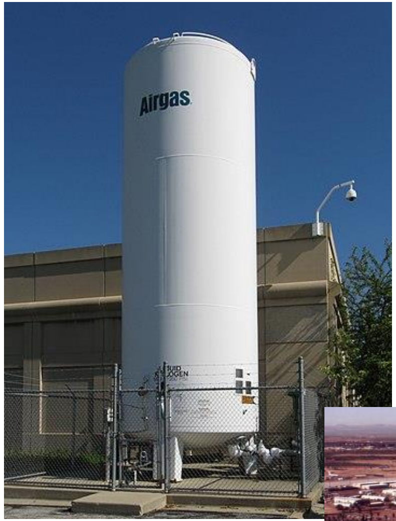


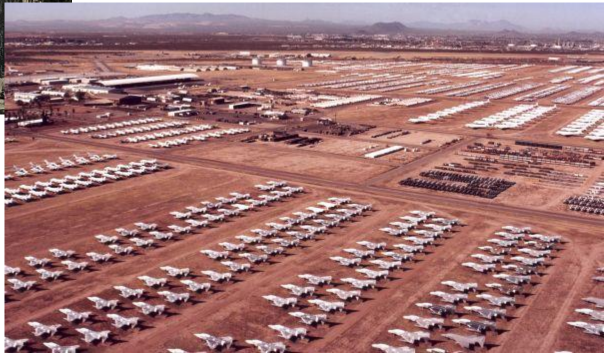

Stock Flow Diagram



# Inventory, Store, and Warehouse





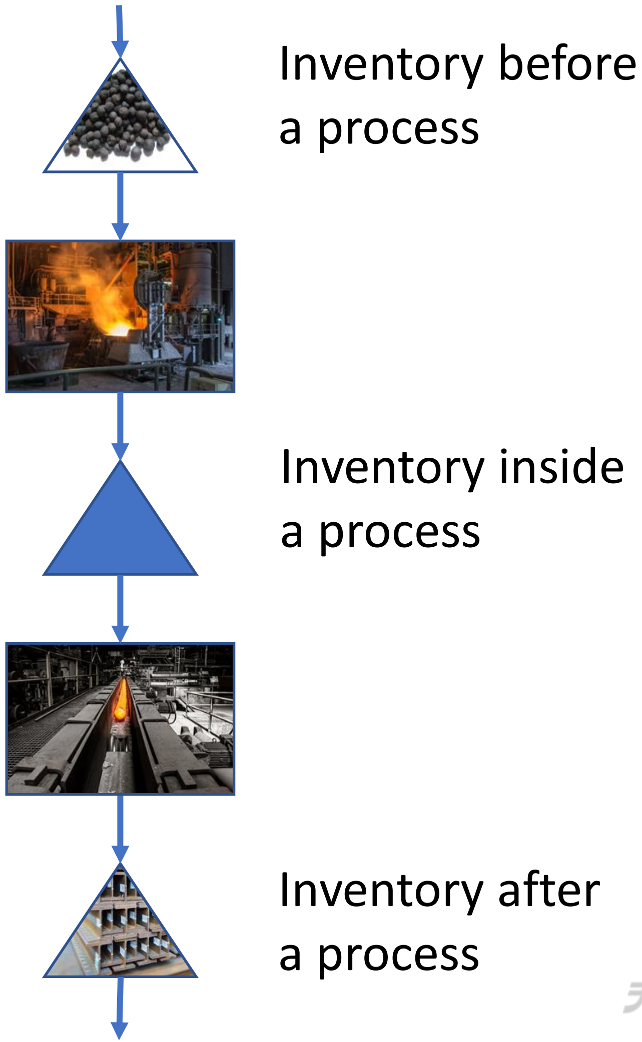



# Management of Inventories

Right quantity of the right product in the right place at the right time

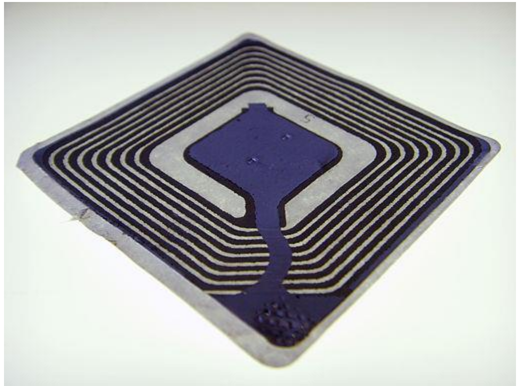
# Types of Inventory

- Raw material inventory
- Work-in process inventory (WIP)
- Finished product inventory



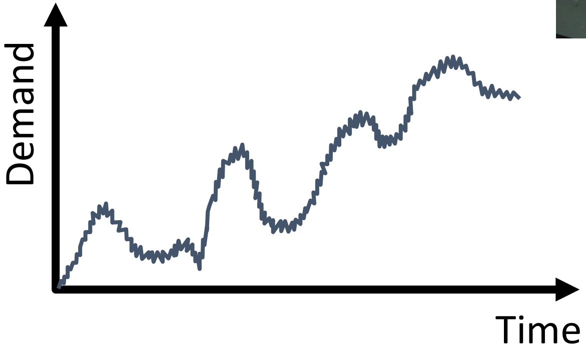
# Inventory Management Capabilities

- Forecasting
- Product and demand tracking
- Analytical skills
- Product transportation and handling assets



# Reasons for Holding Inventories

$$I = R \cdot T$$




- Flow time
- Seasonality (in combination with rigid capacity)
- Batching
- Buffers
- Uncertain demand
- Pricing

# HOW TO MEASURE INVENTORY

# Bakery „Backhaus Heislitz“

- Family business since 1886
- New production building in Kriftel (opening 2012)
- Approx. 100 employees
- 10 locations
- 12 types of rolls
- Aroma cupboard for „maturing“ bread roll dough

 https://heislitz.de/

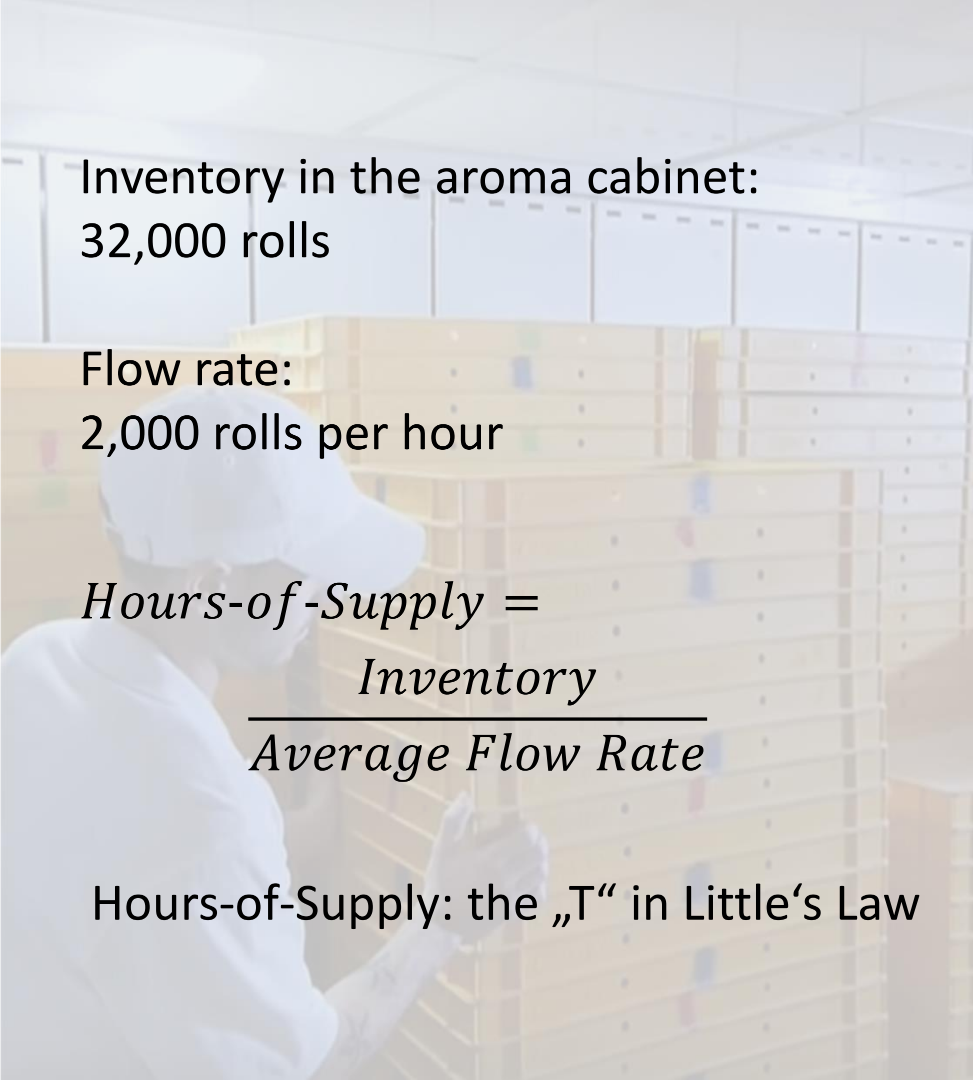
# Backhaus Heislitz Challenges

- What is the hours-of-supply for the inventory in the „aroma cupboard“?

- What is the inventory turnover for the aroma cupboard?

# Backhaus Heislitz
# Challenges

$$\text{Hours-of-Supply} =$$



Inventory in the aroma cabinet:
32,000 rolls

Flow rate:
2,000 rolls per hour

$$Hours\text{-}of\text{-}Supply = \frac{Inventory}{Average\ Flow\ Rate}$$

Hours-of-Supply: the „T“ in Little‘s Law

# Backhaus Heislitz Challenges

$$Inventory =$$

$$Average\ Flow\ Rate =$$

$$Hours\text{-}of\text{-}Supply =$$

Inventory in the aroma cabinet:

- 25,000 Urweck
- 7,000 Krustis

Flow rates:

- 1,500 Urweck per hour
- 500 Krustis per hour

Production costs:

- 0.20 € per Urweck
- 0.40 € per Krusti

$$Hours\text{-}of\text{-}Supply = \frac{Stock}{Average\ Flow\ Rate}$$

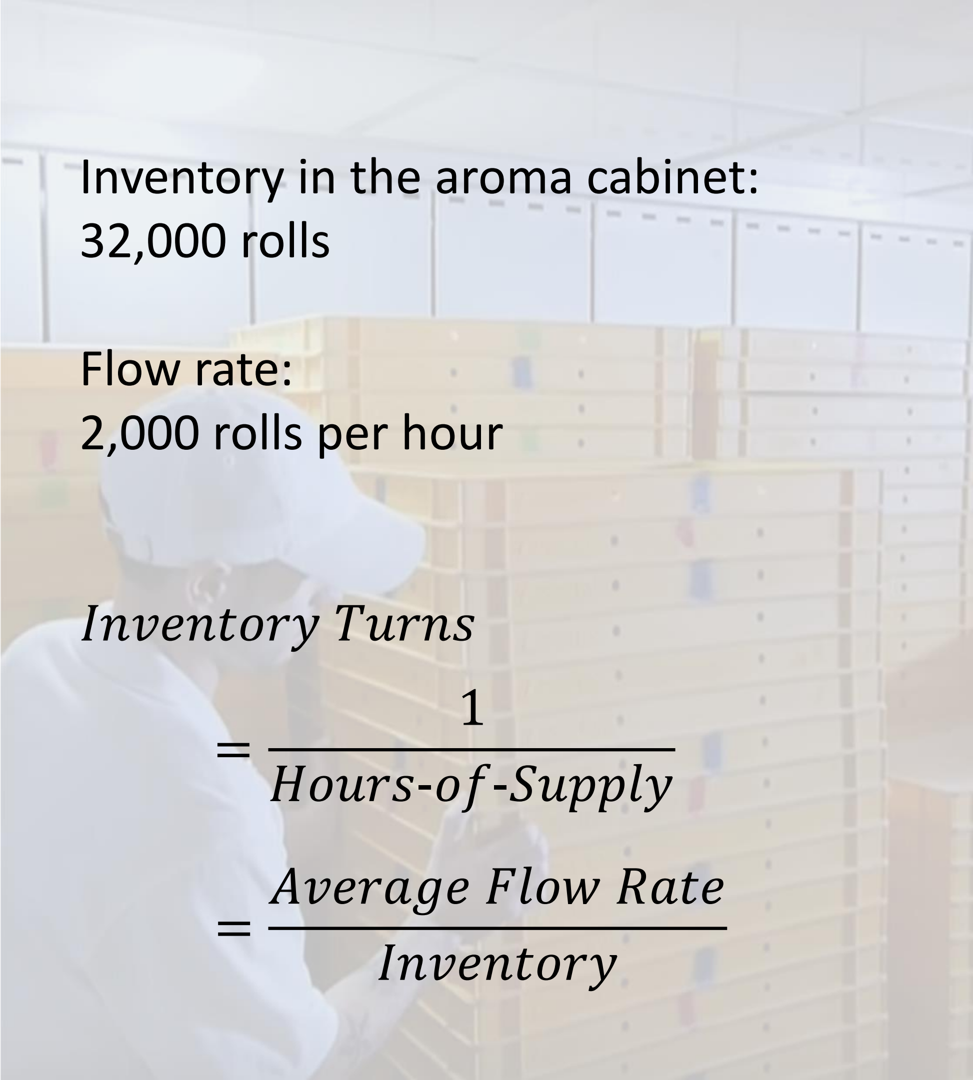
# Backhaus Heislitz Challenges

- What is the hours-of-supply for the inventory in the „aroma cupboard"?

- What is the inventory turnover for the aroma cupboard?

# Backhaus Heislitz Challenges

$$Inventory\ Turns =$$



Inventory in the aroma cabinet:
32,000 rolls

Flow rate:
2,000 rolls per hour

$$Inventory\ Turns$$

$$= \frac{1}{Hours\text{-}of\text{-}Supply}$$

$$= \frac{Average\ Flow\ Rate}{Inventory}$$

# Benchmark – Inventory Turns for Retail Segments

| Retail Segment | Examples | Annual Inventory Turns [1/Years] | Days-of-Supply [Days] |
|---|---|---|---|
| Jewelry | Tiffany | 1.68 | 217 |
| Hobby, toy/game stores | Toys R Us | 2.99 | 122 |
| Department store | Sears, JCPenney | 3.87 | 94 |
| Radio, TV, consumer electronics | Best Buy | 4.10 | 89 |
| Variety stores | Johl's, Target | 4.45 | 82 |
| Apparel and accessory | Ann Taylor, Gap | 4.57 | 80 |
| Drug and proprietary stores | Rite Aid, CVS | 5.26 | 69 |
| Home furniture/equipment | Bed Bath & Beyond | 5.44 | 67 |
| Catalog, mail-order | Spiegel, Lands' End | 8.60 | 42 |
| Food stores | Safeway, Walmart | 10.78 | 34 |

Cachon/Terwiesch, 2020, S. 304

# Benchmark – Inventory Turns for Selected Retailers

| Company | Categories | Annual Inventory Turns | Days-of-Supply |
|---|---|---|---|
| Macy's | Apparel, cosmetcs, home furnishings | 3.1 | 117 |
| Kohl's | Apparel, footwear, soft home products | 3.3 | 111 |
| Lowe's | Hardware, home improvement | 3.9 | 95 |
| Sears | Hardware, apparel, home furnishings, appliances | 3.9 | 94 |
| Home Depot | Hardware, home improvement | 4.6 | 80 |
| Ace Hardware | Hardware | 6 | 60 |
| Target | Apparel, grocery, home furnishings, electronics | 6.4 | 57 |
| Walmart | Apparel, grocery, home furnishings, electronics | 8.2 | 44 |
| Costco | Apparel, grocery, home furnishings, electronics | 12.2 | 30 |
| Kroger | Grocery | 12.3 | 30 |
| Safeway | Grocery | 12.7 | 29 |
| SuperValu | Grocery | 17.3 | 21 |
| Whole Foods | Grocery | 20.2 | 18 |

Cachon/Terwiesch, 2020, p. 304

# Covestro

- Leading global supplier of innovative, sustainable and versatile high-tech polymer materials
- Before Sept. 1, 2015 Bayer MaterialScience
- > 1.000 products, 16.500 employees
- Headquarters: Leverkusen


 https://www.covestro.com/

# Covestro Challenges

- What is Covestro’s Years-of-Supply measure for 2019 and 2020?
- What is Covestro’s Inventory Turnover measure for 2019 and 2020?

## Covestro – Annual Report 2019

### Covestro Group Consolidated Statement of Financial Position

| | Dec. 31, 2019 | Dec. 31, 2020 |
|---|---|---|
| | € million | € million |
| **Current assets** | | |
| Inventory | 1,916 | 1,663 |
| Trade accounts receivable | 1,561 | 1,593 |
| Other financial assets | 27 | 1144 |
| Other receivables | 359 | 295 |
| Claims for income tax refunds | 104 | 55 |
| Cash and cash equivalents | 748 | 1404 |
| Assets held for sale | 12 | 36 |
| | **4,727** | **6,190** |

### Covestro Group Consolidated Income Statement

| | 2019 | 2020 |
|---|---|---|
| | € million | € million |
| **Sales** | **12,412** | **10,706** |
| Cost of goods sold | -9,658 | -8,207 |
| **Gross profit** | **2,754** | **2,499** |
| Selling expenses | –1.380 | –1.195 |
| Research and development expenses | –266 | –262 |
| General administration expenses | –372 | –310 |
| Other operating income | 181 | 63 |
| Other operating expenses | –65 | –99 |
| **EBIT** | **852** | **696** |

# Covestro Inventory metrics

$$Years\text{-}of\text{-}supply =$$

## Covestro – Annual Report 2019

### Covestro Group Consolidated Statement of Financial Position

| | Dec. 31, 2019 | Dec. 31, 2020 |
|---|---|---|
| | € million | € million |
| **Current assets** | | |
| Inventory | 1,916 | 1,663 |
| Trade accounts receivable | 1,561 | 1,593 |
| Other financial assets | 27 | 1144 |
| Other receivables | 359 | 295 |
| Claims for income tax refunds | 104 | 55 |
| Cash and cash equivalents | 748 | 1404 |
| Assets held for sale | 12 | 36 |
| | **4,727** | **6,190** |

### Covestro Group Consolidated Income Statement

| | 2019 | 2020 |
|---|---|---|
| | € million | € million |
| **Sales** | **12,412** | **10,706** |
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# Covestro Inventory metrics

$$Inventory\ Turns =$$

## Covestro – Annual Report 2020

### Covestro Group Consolidated Statement of Financial Position

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# STOCKOUT AND HOLDING COSTS

# Consequences of a Stockout

- Customer waits for the item to become available
- Lose the sale of one item, but the customer purchases another item
- Lose the sale
- Lose the sale and lose the customer

# Stockout Cost

- Stockout costs are opportunity costs
- Opportunity costs are difficult to determine
- A company needs to know where it is on the „stockout cost spectrum“

# Inventory Holding Cost

- Opportunity cost of capital
- Inventory storage cost
- Obsolescence cost
- Spoilage and shrinking cost

# Inventory Holding Cost Percentage and per Unit

- Inventory holding cost percentage $h_p$: ratio of the cost to hold an item in inventory during a designated time period relative to the cost c to purchase the item.
- Inventory holding cost per unit h: cost to hold an item in inventory during a designated time period.

$$h = h_p \cdot c$$

Example:
If an item costs € 50 and the firm assigns an annual holding cost percentage of 30%, then it costs the firm 0.3 · € 50 = € 15 to hold that item in inventory for an entire year.

# Inventory Holding Cost for One Single Unit

**Question:**

How much does it cost the retailer to hold a dress that it purchased for 50€?

**Data:**

- The holding cost of inventory at a retailer is 35 % per year.
- The retailer's annual turns are 3.

**Antwort:**

Holding Cost for one year:

The dress is not in stock for whole year:

Holding Cost for one dress:

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# INVENTORY MANAGEMENT WITH STEADY DEMAND

# THE ECONOMIC ORDER QUANTITY

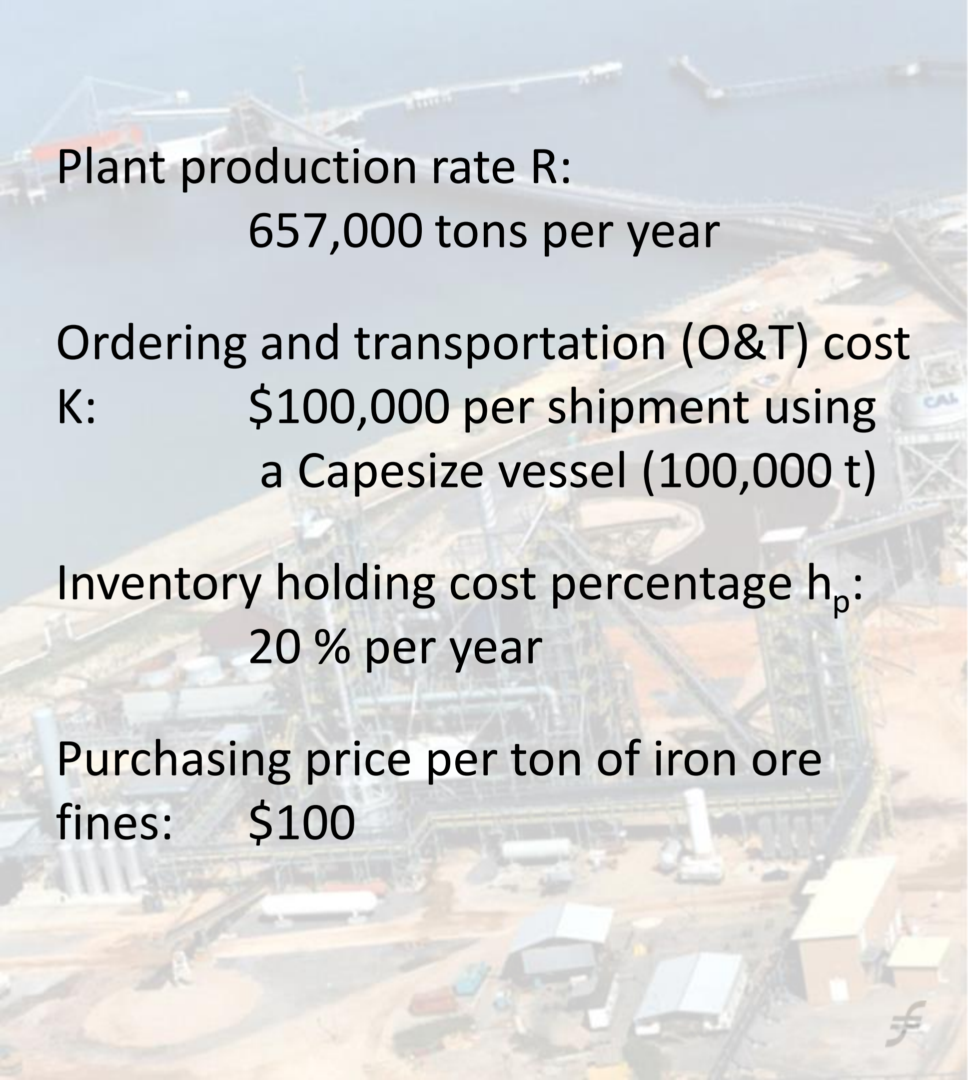
# Circored Iron Ore Reduction Plant

- Iron ore fines is purchased from ore mines in South America
- Circored process uses hydrogen to reduce the ore
- Direct Reduced Iron (DRI) is briquetted to produce Hot Briquetted Iron (HBI)
- Plant output (HBI): sold to steel mills known as “mini-mills”

Nuber et al, 2006; Loch & Terwiesch, 2002

# Iron Ore Reduction Plant Challenges

- What is the yearly cost of ordering and transporting iron ore fines?
- What is the yearly cost of holding iron ore fines inventory?
- What is the cost minimal order quantity?
- How often is an order placed?



Plant production rate R:
657,000 tons per year

Ordering and transportation (O&T) cost K: $100,000 per shipment using a Capesize vessel (100,000 t)

Inventory holding cost percentage $h_p$:
20 % per year

Purchasing price per ton of iron ore fines: $100

# Annual Ordering and Transportation Cost

$$\mathit{Annual\ O\&T\ Cost}\ C_{OT}$$

$$= K \cdot \frac{R}{Q}$$

Plant production rate R:
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Ordering and transportation (O&T) cost K: $100,000 per shipment using a Capesize vessel (100,000 t)

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# Iron Ore Reduction Plant Challenges

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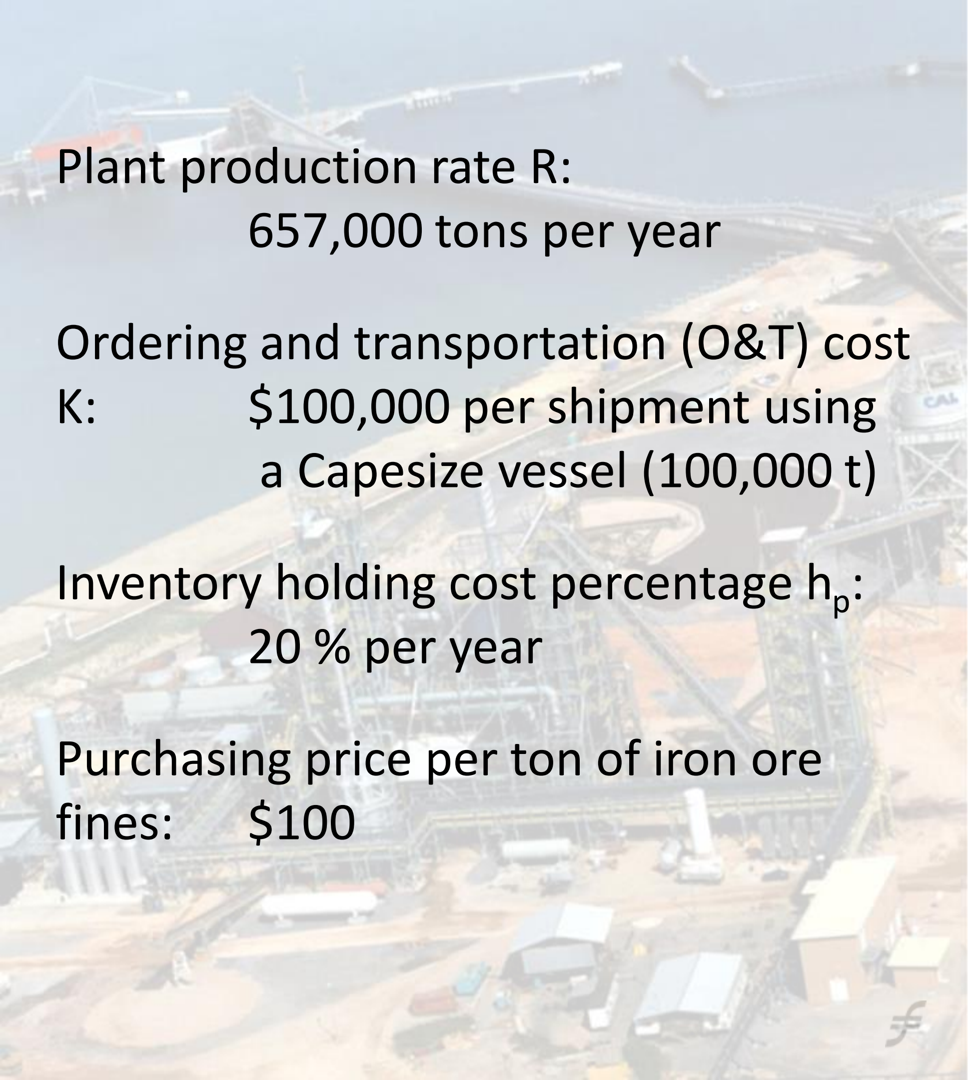

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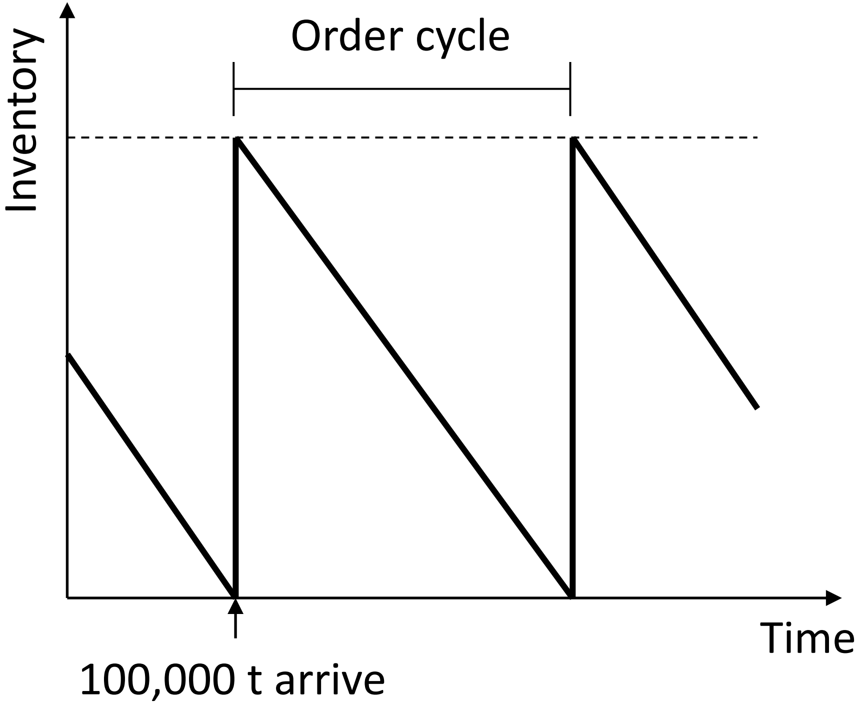
# Annual Inventory Holding Costs




Order time = Delivery time (since Delivery time = 0)

Plant production rate R:
657,000 tons per year

Ordering and transportation (O&T) cost K: $100,000 per shipment using a Capesize vessel (100,000 t)

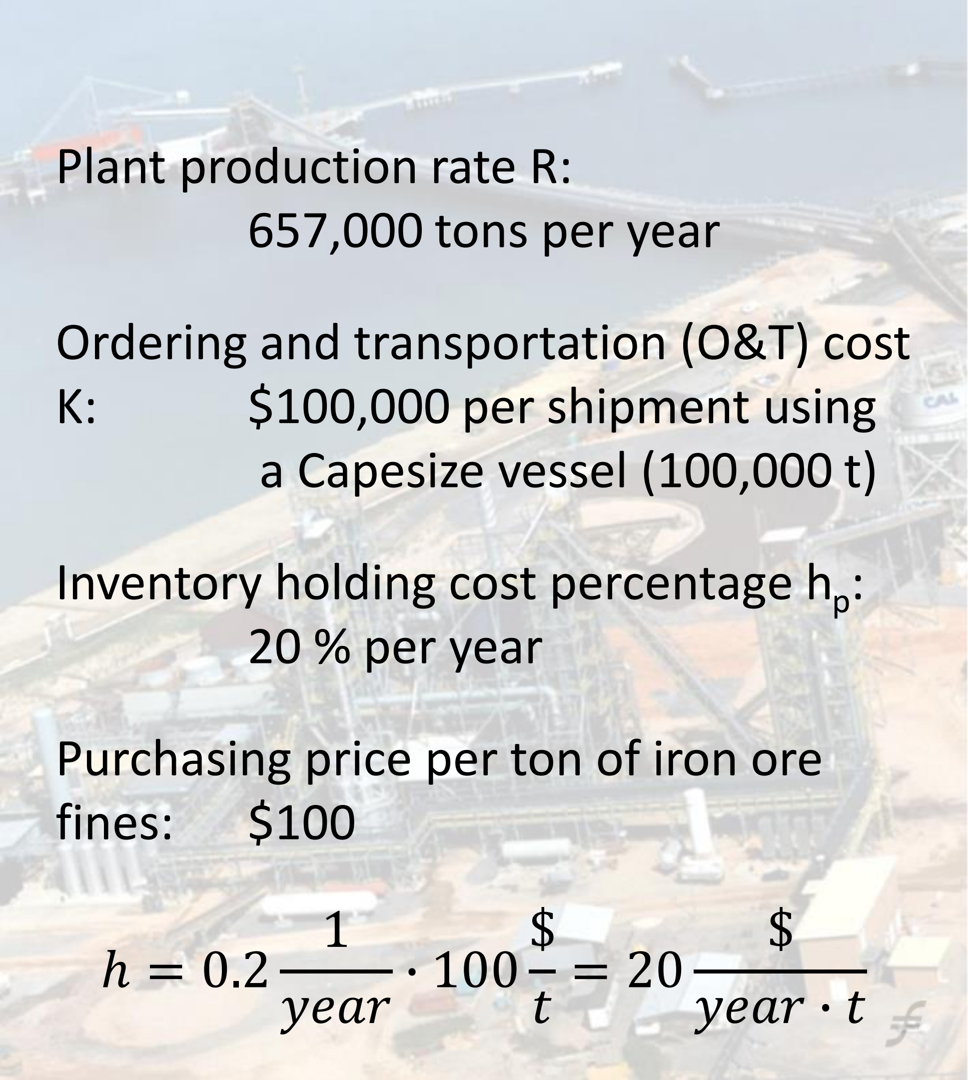
Inventory holding cost percentage $h_p$:
20 % per year

Purchasing price per ton of iron ore fines: $100

# Annual Inventory Holding Costs

$$Annual\ inventory\ holding\ cost\ C_H$$

$$= \frac{1}{2} \cdot h \cdot Q$$



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Inventory holding cost percentage $h_p$:
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Purchasing price per ton of iron ore fines: $100

$$h = 0.2 \frac{1}{year} \cdot 100 \frac{\$}{t} = 20 \frac{\$}{year \cdot t}$$

# Iron Ore Reduction Plant Challenges

- What is the yearly cost of ordering and transporting iron ore fines?
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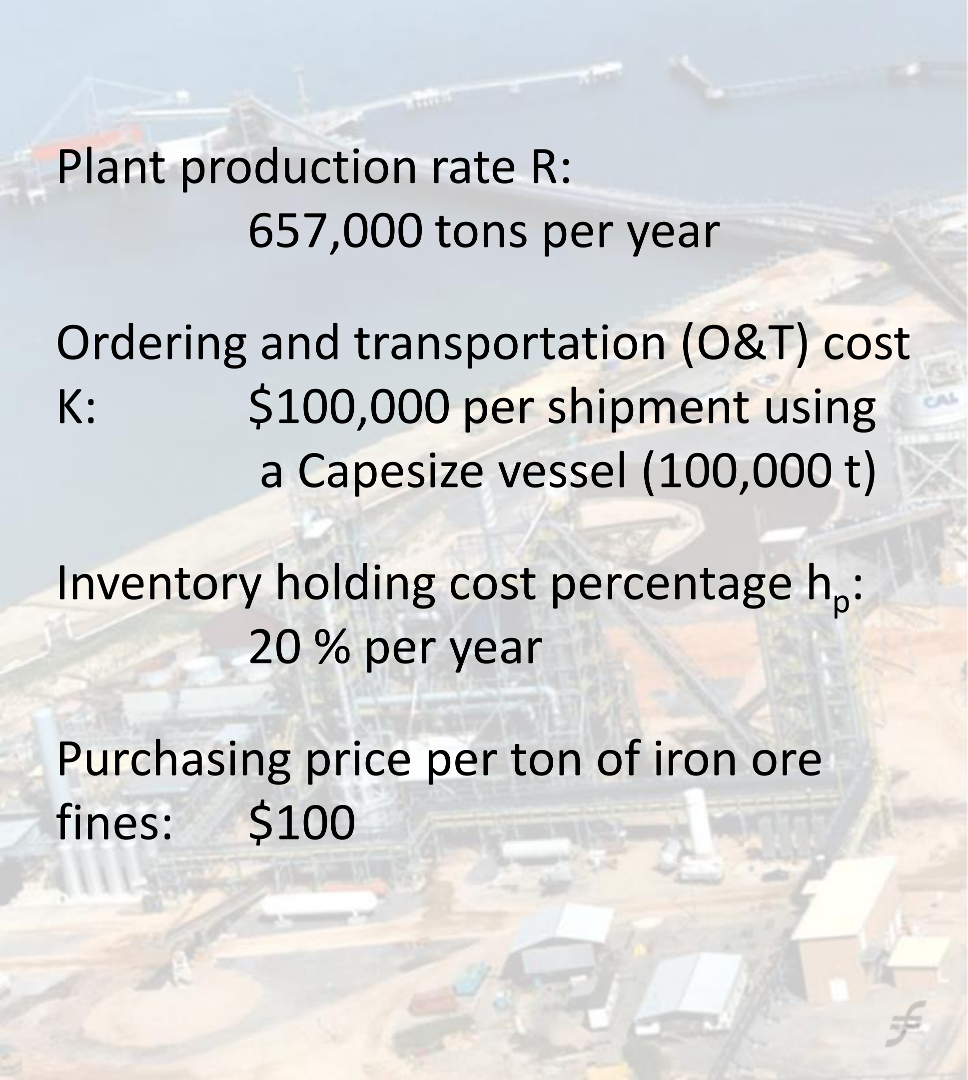
- How often is an order placed?



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20 % per year

Purchasing price per ton of iron ore fines: $100

# Optimal Order Quantity

Minimize total annual inventory holding and O & T costs C(Q)

$$C(Q) = \frac{1}{2} \cdot h \cdot Q + K \cdot \frac{R}{Q} \overset{!}{\rightarrow} min$$

(1) $\frac{dC(Q)}{dQ} = 0$

(2) $\frac{1}{2} \cdot h - K \cdot \frac{R}{Q^2} = 0$

(3) $K \cdot \frac{R}{Q^2} = \frac{1}{2} \cdot h$

(4) $\frac{1}{Q^2} = \frac{1}{2} \cdot h \frac{1}{R \cdot K}$

(5) $Q^2 = \frac{2 \cdot R \cdot K}{h}$

(6) $Q^* = \sqrt{\frac{2 \cdot R \cdot K}{h}}$

# Optimal Order Quantity

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

Plant production rate R:
657,000 tons per year

Ordering and transportation (O&T) cost K: $100,000 per shipment using a Capesize vessel (100,000 t)

Inventory holding cost percentage $h_p$:
20 % per year

Purchasing price per ton of iron ore fines: $100

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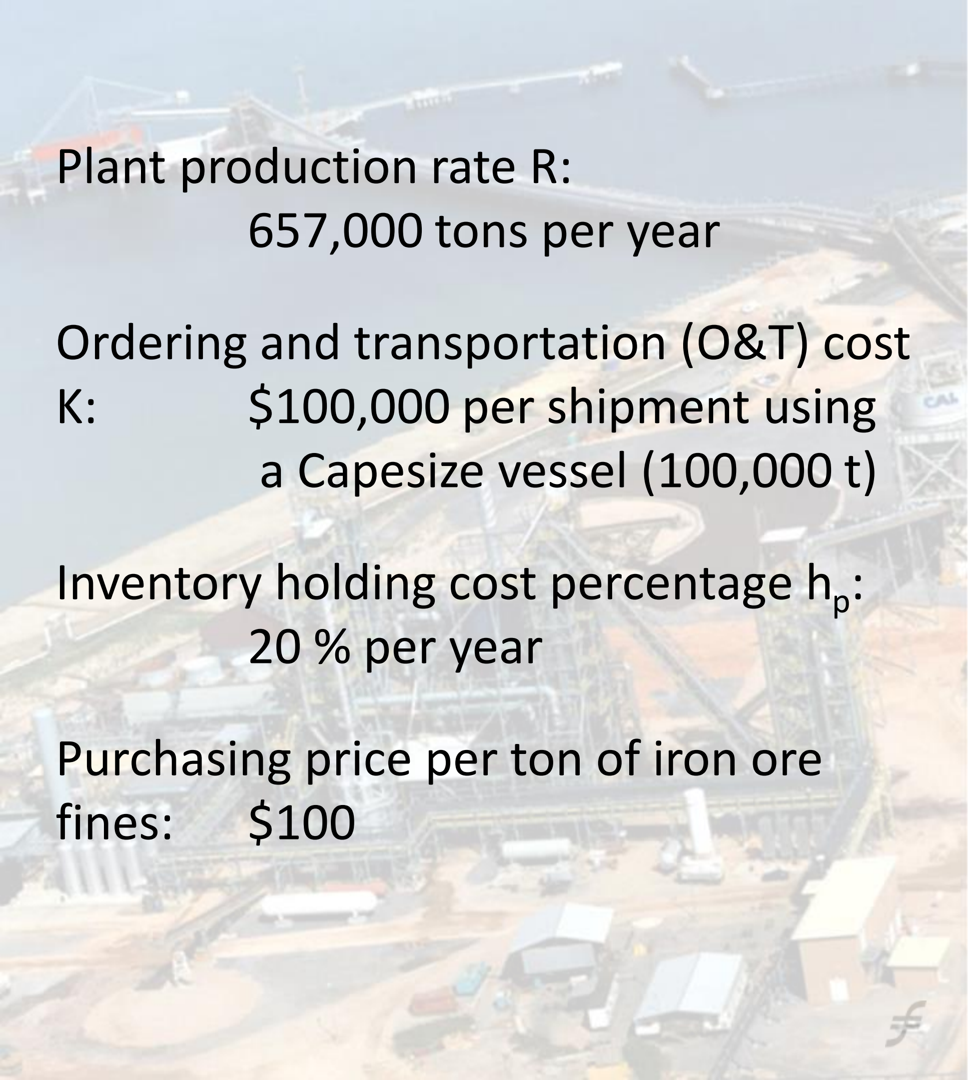
# Iron Ore Reduction Plant Challenges

- What is the yearly cost of ordering and transporting iron ore fines?
- What is the yearly cost of holding iron ore fines inventory?
- What is the cost minimal order quantity?
- **How often is an order placed?**



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Ordering and transportation (O&T) cost K: $100,000 per shipment using a Capesize vessel (100,000 t)

Inventory holding cost percentage $h_p$: 20 % per year

Purchasing price per ton of iron ore fines: $100

# Order frequency

$$Order\ frequency = \frac{Flow\ rate\ R}{Order\ quantity\ Q}$$

Plant production rate R:
657,000 tons per year

Ordering and transportation (O&T) cost K: $100,000 per shipment using a Capesize vessel (100,000 t)

Inventory holding cost percentage $h_p$:
20 % per year

Purchasing price per ton of iron ore fines: $100

# Optimal Annual Total Cost C(Q*)

$$C(Q^*) = \frac{1}{2} \cdot h \cdot Q^* + K \cdot \frac{R}{Q^*}$$

$$Q^* = 36{,}249.14t$$

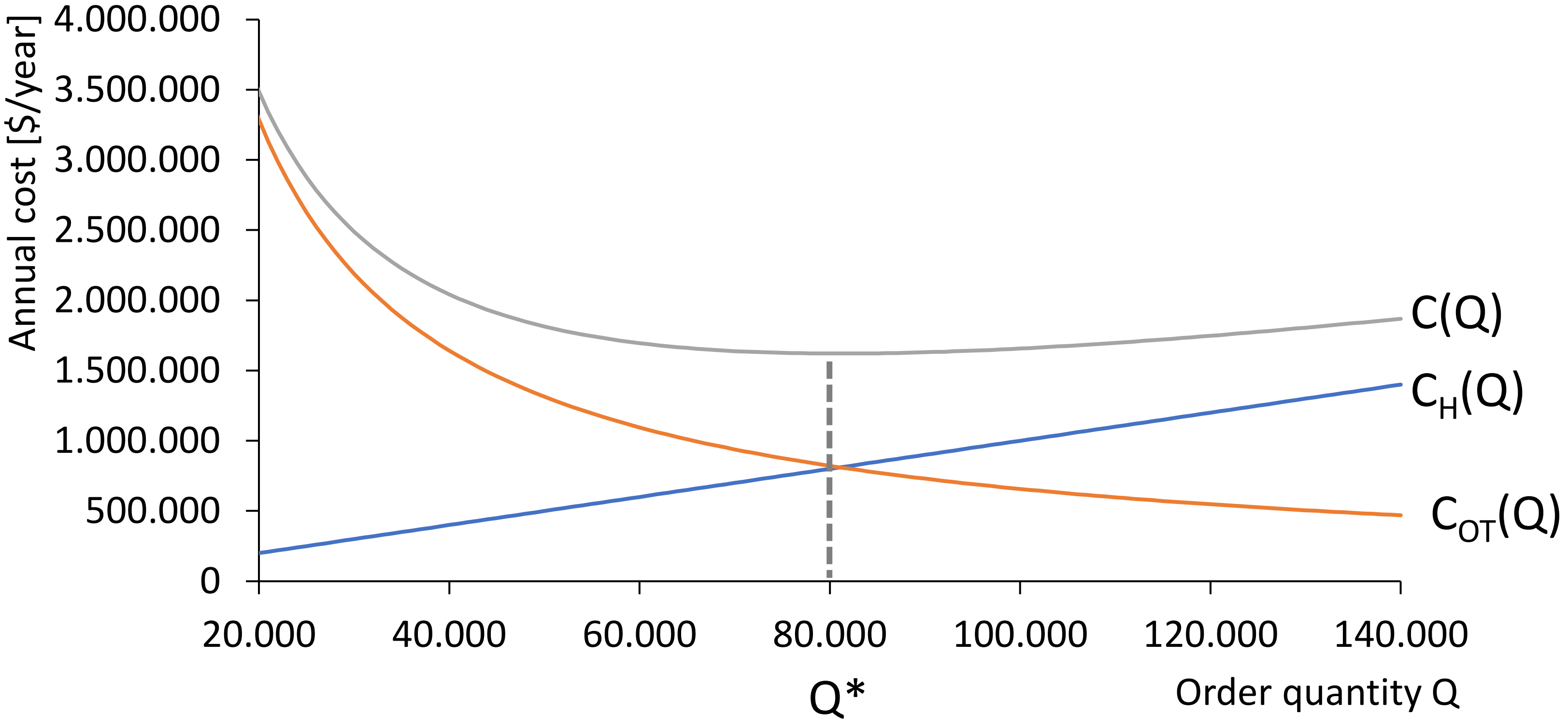
$$h = 0.2 \frac{1}{year} \cdot 500 \frac{\$}{t}$$

$$= 100 \frac{\$}{year \cdot t}$$

$$K = 100{,}000\$$$

$$R = 657{,}000 \frac{t}{year}$$

# EOQ Costs as a Function of Q



# Xootr LLC Handle Caps Purchasing Challenge

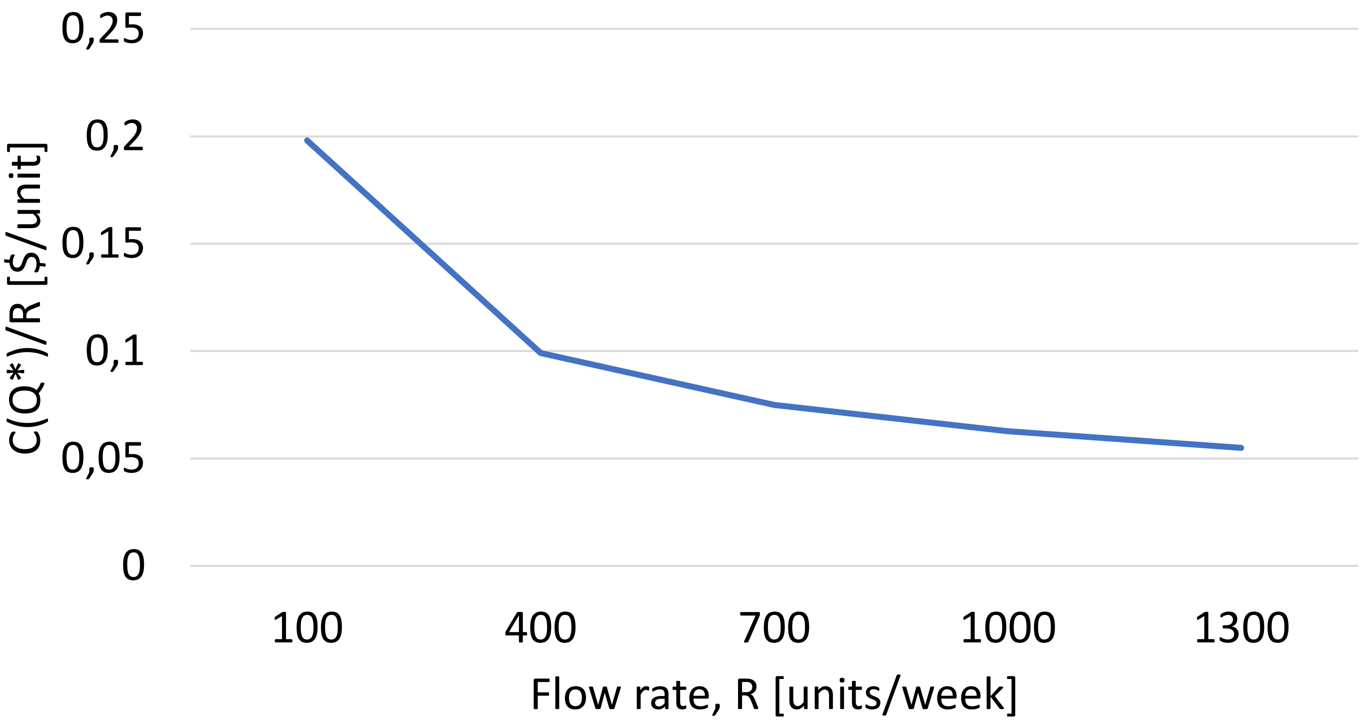
- Xootr LLC purchases pairs of handle caps from a supplier in Taiwan for $0.85 per pair
- Ordering and transportation from Taiwan to the US is $300 per shipment
- Production rate is 700 Xootr/week
- Annual inventory holding cost percentage is 40%




https://www.xootr.com/

# What is the optimal caps EOQ? What is C(Q*)?

# EOQ and Economies of Scale



# QUANTITY CONSTRAINTS AND DISCOUNTS

# Xootr LLC Handle Caps Purchasing Challenge

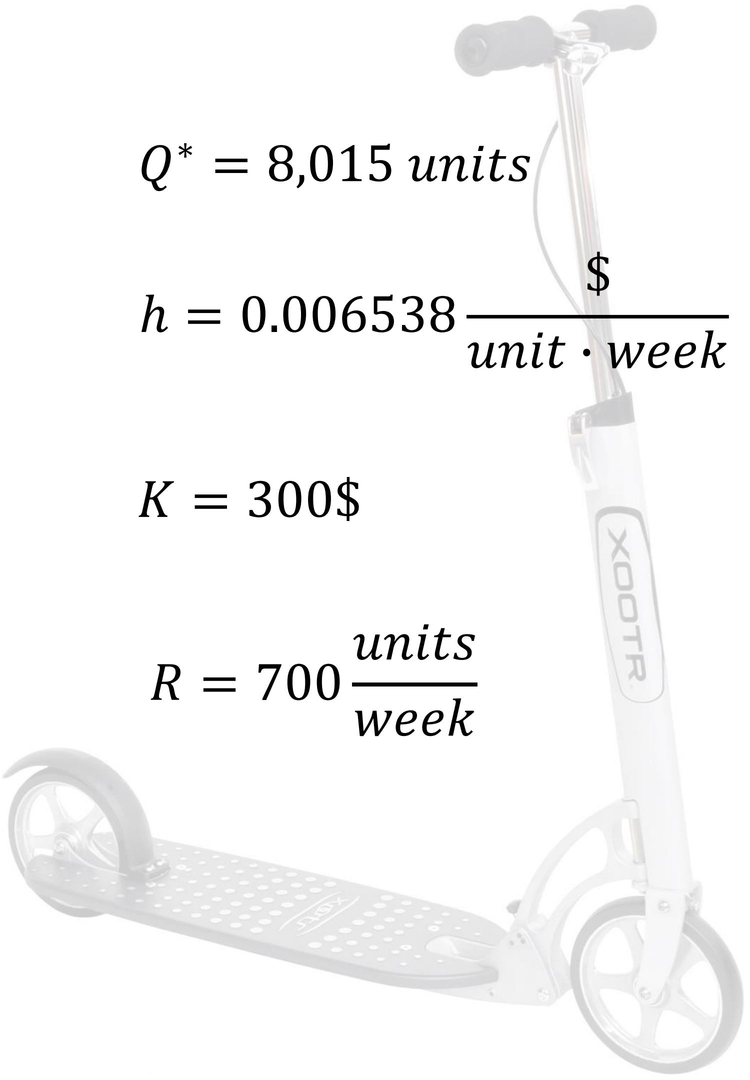
- What is the impact of order quantity constraints on Q?
- Should the Xootr purchasing manager accept a price discount for a higher Q than the EOQ or not?




https://www.xootr.com/

# Xootr LLC Handle Caps Purchasing Challenge

- What if handle caps need to be ordered in boxes containing 5,000 units?




$$Q^* = 8{,}015\ units$$

$$h = 0.006538 \frac{\$}{unit \cdot week}$$

$$K = 300\$$$

$$R = 700 \frac{units}{week}$$



https://www.xootr.com/

# Xootr LLC Handle Caps Purchasing Challenge

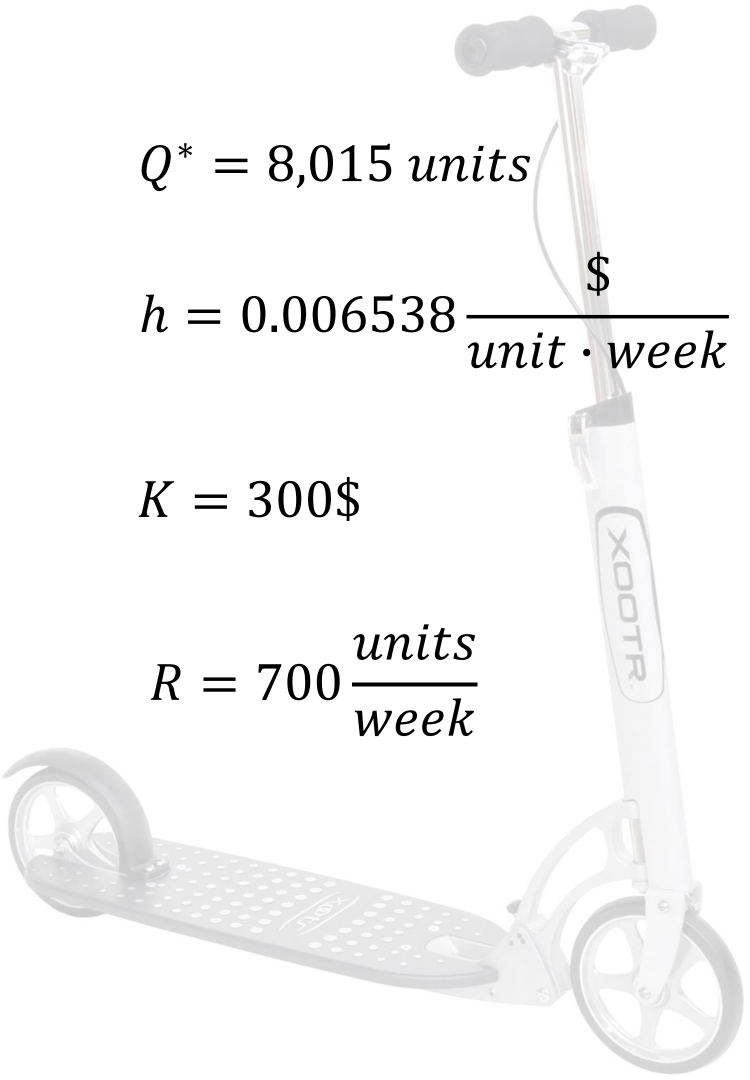
- Should the Xootr purchasing manager order 10,000 units if this gets them a 5% discount from the supplier?

$$Q^* = 8{,}015\ units$$

$$h = 0.006538 \frac{\$}{unit \cdot week}$$

$$K = 300\$$$

$$R = 700 \frac{units}{week}$$





https://www.xootr.com/

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# 2023 Operations Management

# INVENTORY MANAGEMENT WITH PERISHABLE DEMAND

# THE NEWSVENDOR MODEL

# Fruchtknall

- Family business proposing

  Ripe fruits
  + highest quality
  + fast transport
  = unique taste
- Direct import from Thailand with express airfreight
- Unique shopping experience
  - Order terminals
  - <15 minutes delivery time



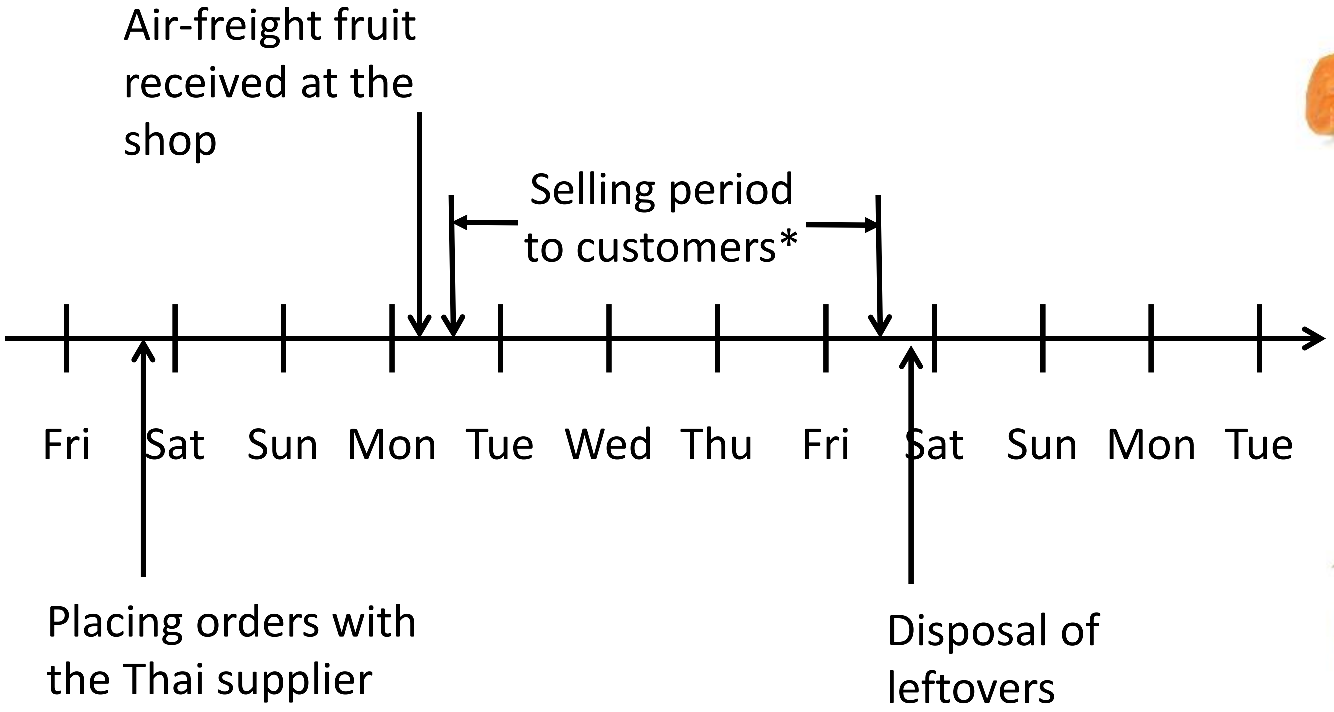
Inspired by https://www.fruchtknall.de/

# Fruchtknall Data

| | Mango | Papaya |
|---|---|---|
| Selling price | 6.00 | 13.00€/unit |
| Purchase price | 3.50 | 2.50€/unit |
| Salvage value | 0.00 | 0.00€/unit |
| Salvage cost | 0.00 | 0.00€/unit |

Inspired by https://www.fruchtknall.de/

# Fruchtknall Air-freight Fruit Timeline




* Uncertain demand, sale as long as stock lasts

# Fruchtknall Challenge

- How is the profit contribution of a specific week calculated?
- Ordering how many mangos and papayas maximizes weekly profit contributions?

# A Week's Profit Contribution

$$Profit_{Mango} =$$

$$Profit_{Papya} =$$

Demand and order quantity of last week:

| | Mango | Papaya | |
|---|---|---|---|
| Demand | 130 | 8 | Unit/Week |
| Order quantity | 120 | 10 | Unit/Week |
| Selling price | 6.00 | 13.00 | Euro/Unit |
| Purchase price | 3.50 | 2.50 | Euro/Unit |

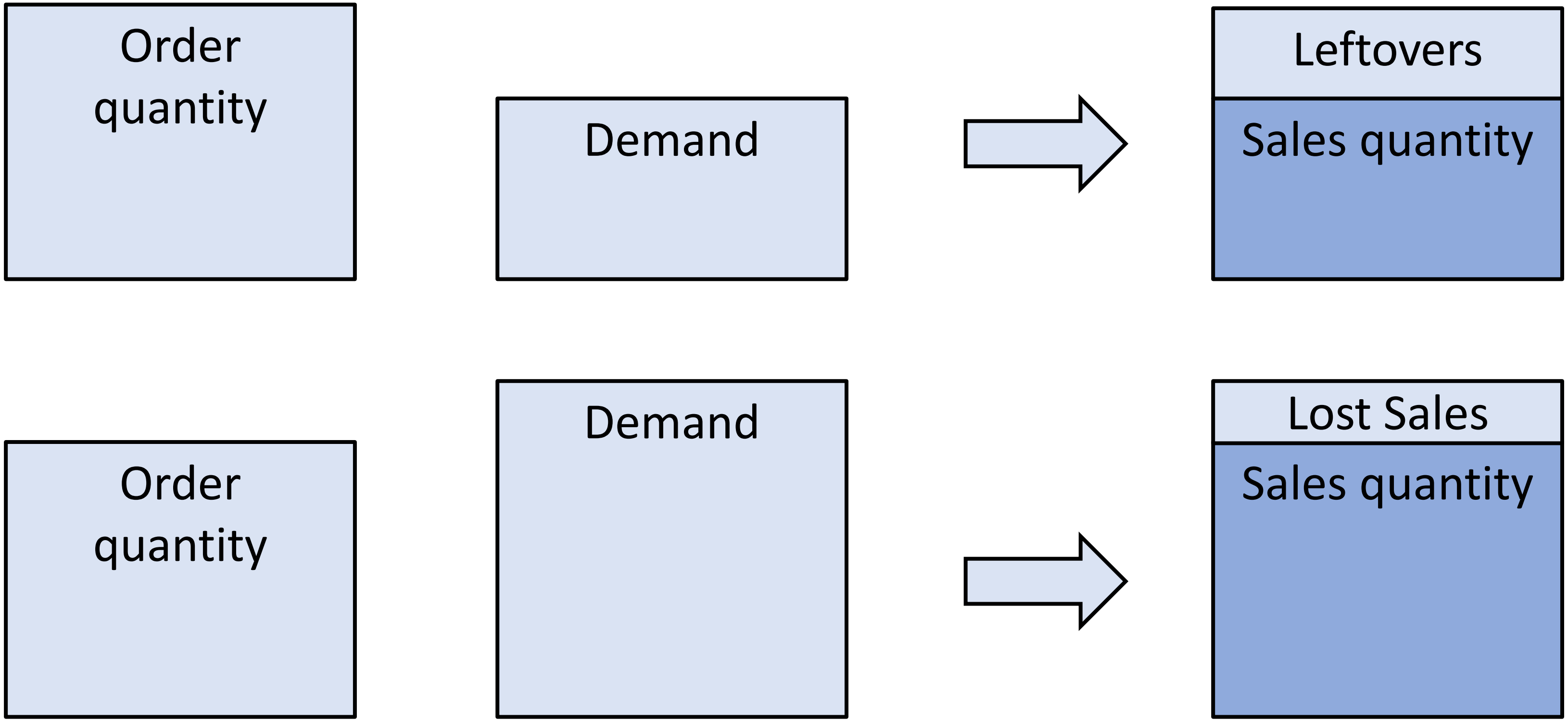
Mangos:
Demand > Order quantity
Sales volume = 120 unit

Papayas:
Demand < Order quantity
Sales volume = 8 unit

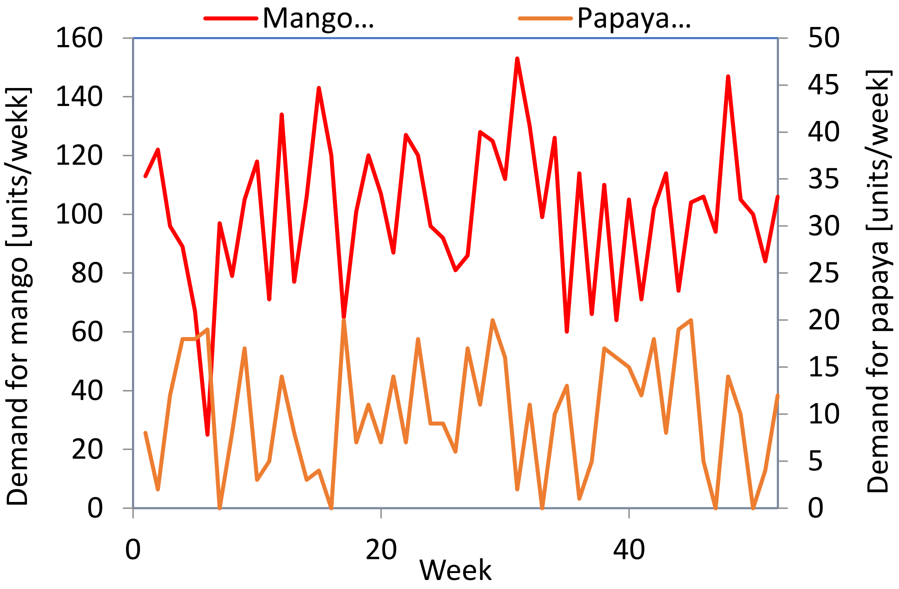
# Fruchtknall Challenge

- How is the profit contribution of a specific week calculated?
- **Ordering how many mangos and papayas maximizes weekly profit contributions?**

# Impact of Orders and Demand on Sales

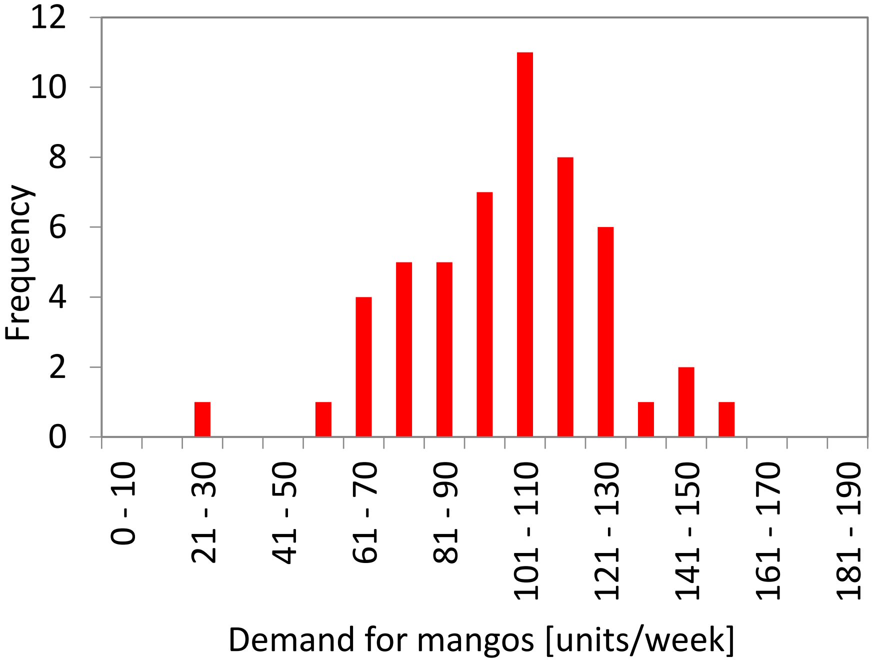


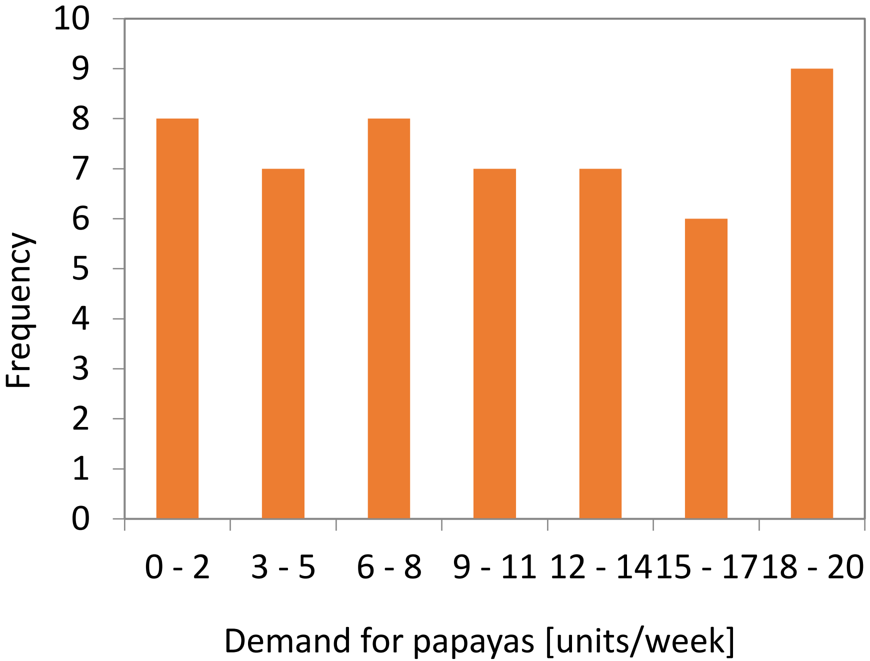
# Forecasting Demand



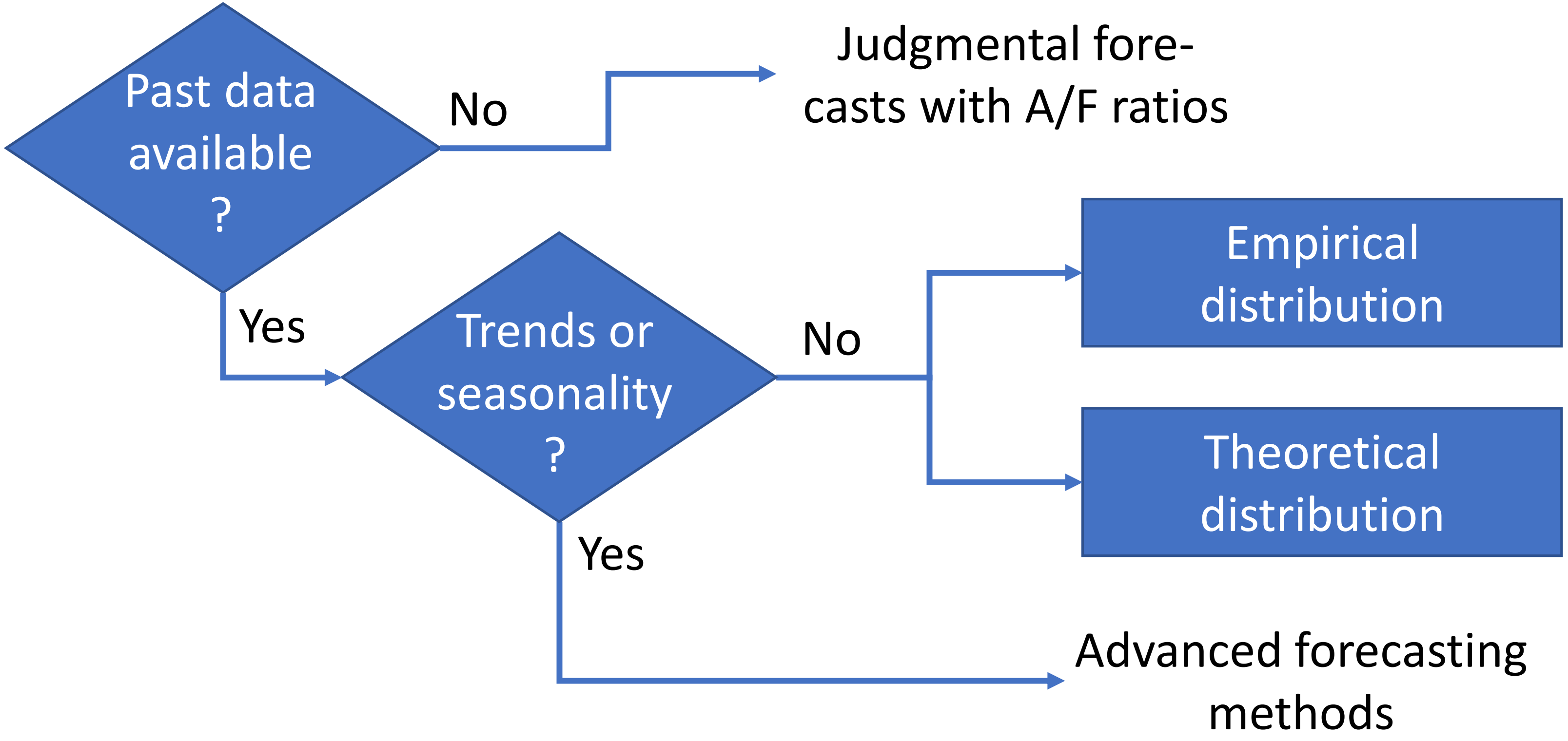

| Week | Mango [units/week] | Papaya [units/week] |
|---|---|---|
| 1 | 113 | 8 |
| 2 | 122 | 2 |
| 3 | 96 | 12 |
| 4 | 89 | 18 |
| 5 | 67 | 18 |
| 6 | 25 | 19 |
| 7 | 97 | 0 |
| 8 | 79 | 8 |
| 9 | 105 | 17 |
| 10 | 118 | 3 |
| 11 | 71 | 5 |
| 12 | 134 | 14 |
| ⋮ | ⋮ | ⋮ |

# Histogram of Past Demand

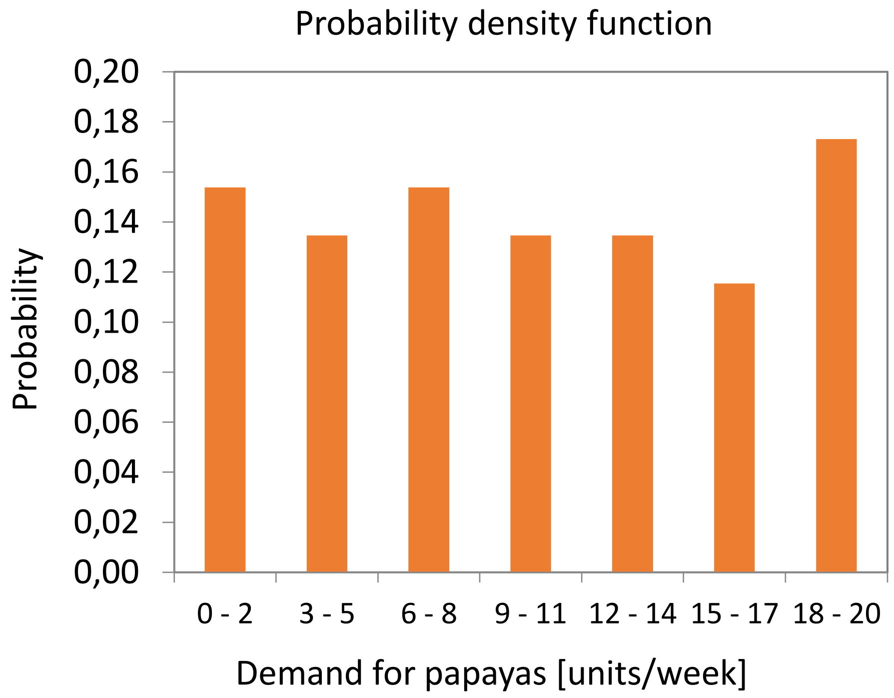


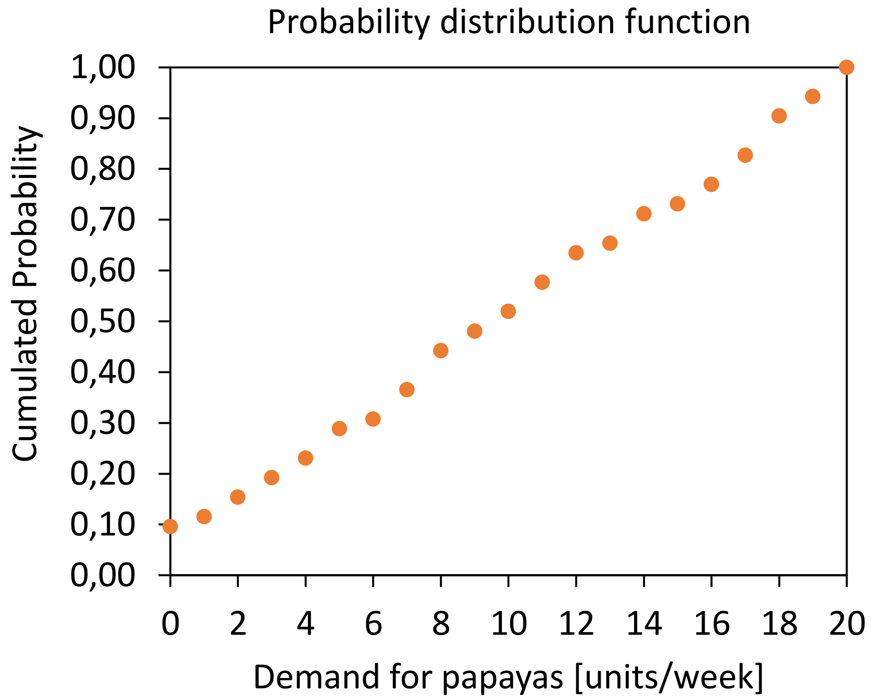



# How to Construct a Forecast for Variable Demand?

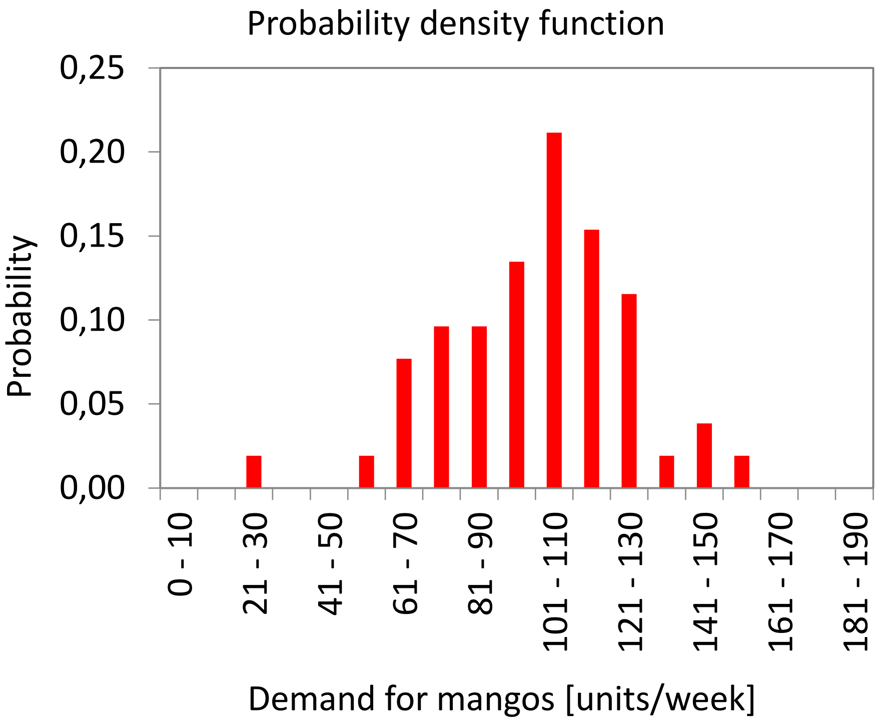


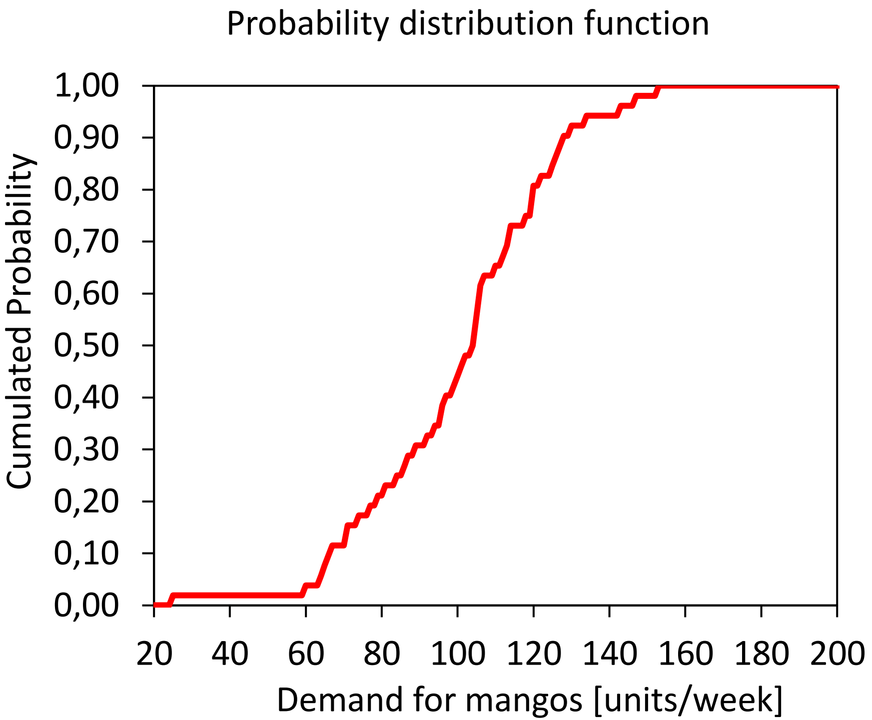
# Empirical Distribution for Papaya Demand



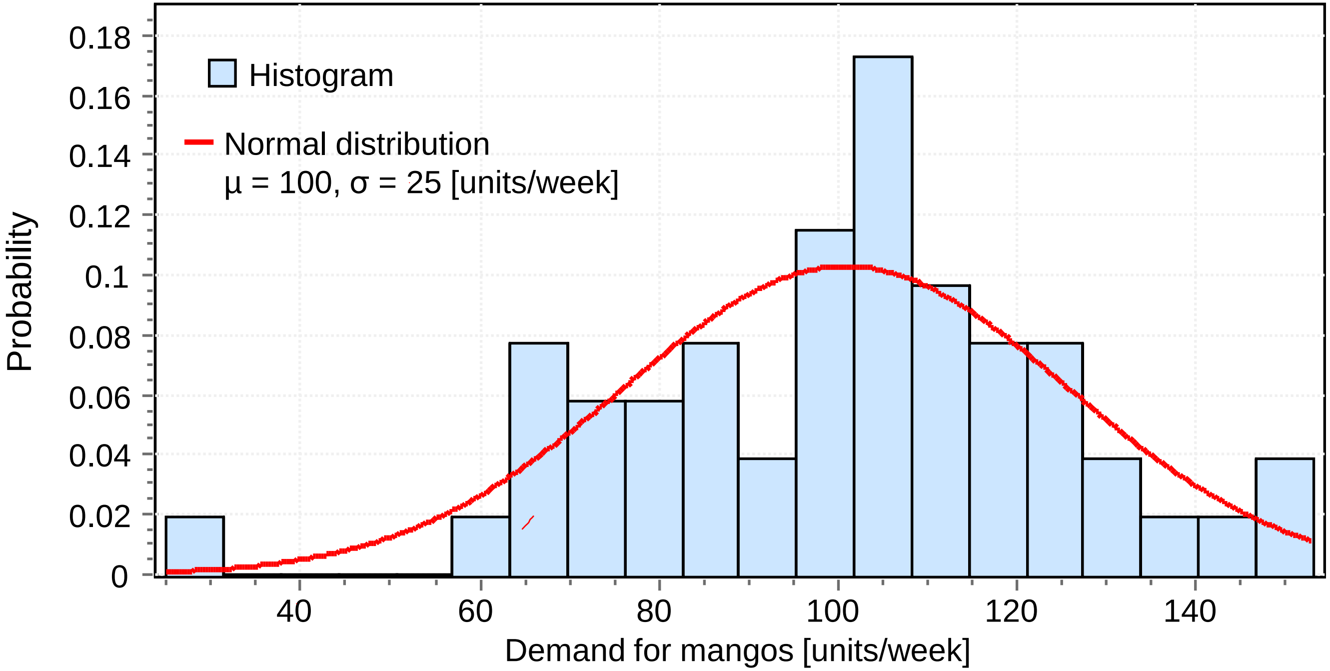



# Empirical Distribution for Mango Demand

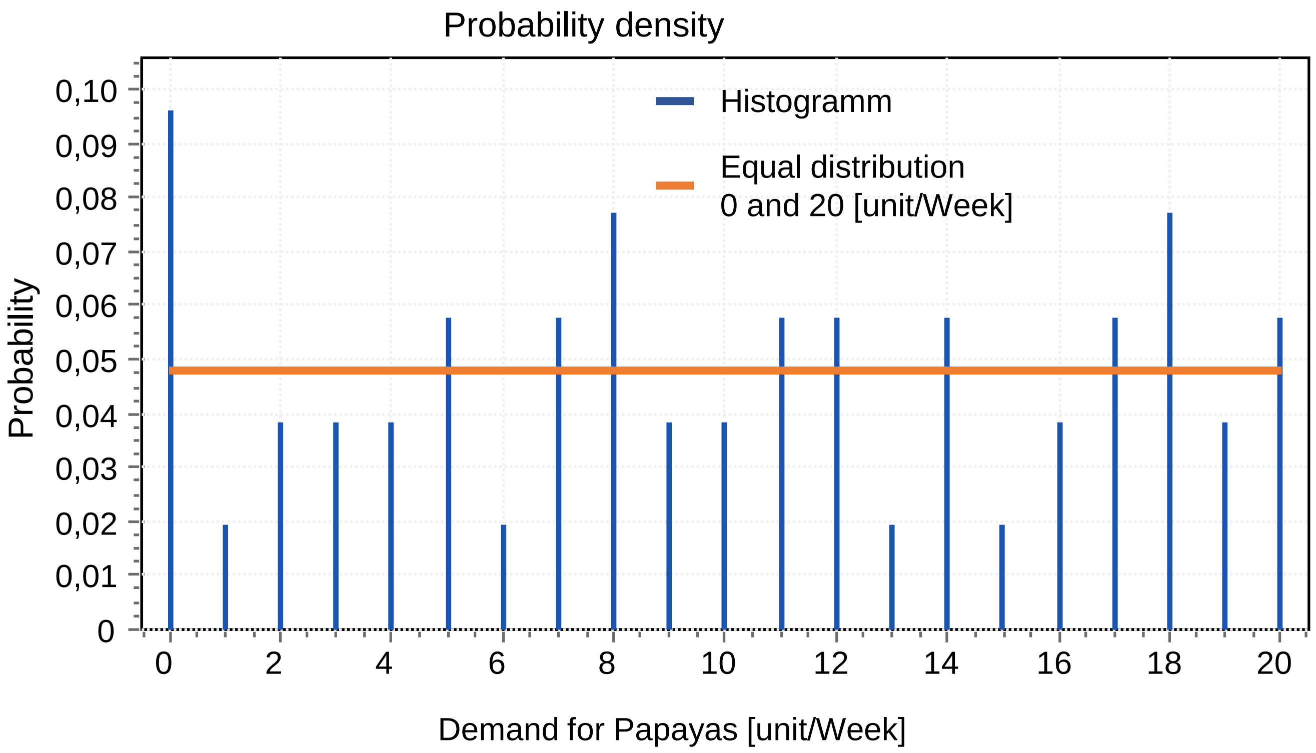


# Fitting a Theoretical Distribution



# Theoretical distribution of Papaya - Demand



# What would you decide?


# Two Ways of Determining Optimal Q*

… taking into account that demand is uncertain.

- Simulation
  - For each possible Q, draw a large number of demand values from the demand distribution and determine profit distribution (average, min, max, stddev)
  - Find the Q that results in the highest – average – profit
  - Type of „brute force approach“
- Analytic
  - Determine an expected profit function (or expected costs functions) that can be solved for the optimal Q

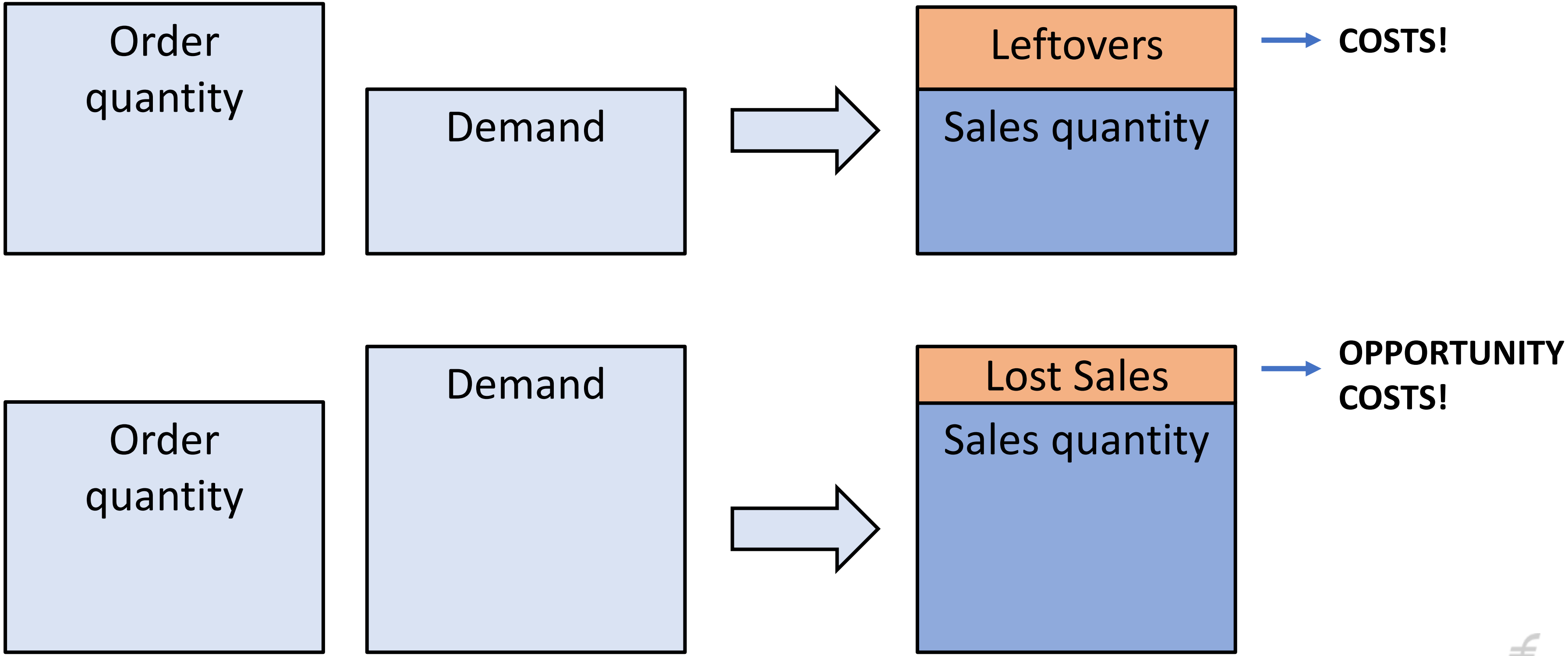
# Simulation with Q = 10 Papayas/week

| | Papaya |
|---|---|
| Selling price | 13.00 €/unit |
| Purchase price | 2.50 €/unit |
| Salvage value | 0.00 €/unit |
| Salvage cost | 0.00 €/unit |

| Repli-cation | Demand [unit/week] | Sales [unit/week] | Lost sales [unit/week] | Leftovers [units/week] | Sales revenue [€/week] | Profit [€/week] |
|---|---|---|---|---|---|---|
| 1 | 18 | 10 | 8 | 0 | 130 | 105 |
| 2 | 16 | 10 | 6 | 0 | 130 | 105 |
| 3 | 19 | 10 | 9 | 0 | 130 | 105 |
| 4 | 2 | 2 | 0 | 8 | 26 | 1 |
| 5 | 15 | 10 | 5 | 0 | 130 | 105 |
| 6 | 19 | 10 | 9 | 0 | 130 | 105 |
| 7 | 14 | 10 | 4 | 0 | 130 | 105 |
| 8 | 5 | 5 | 0 | 5 | 65 | 40 |
| 9 | 4 | 4 | 0 | 6 | 52 | 27 |
| 10 | 11 | 10 | 1 | 0 | 130 | 105 |

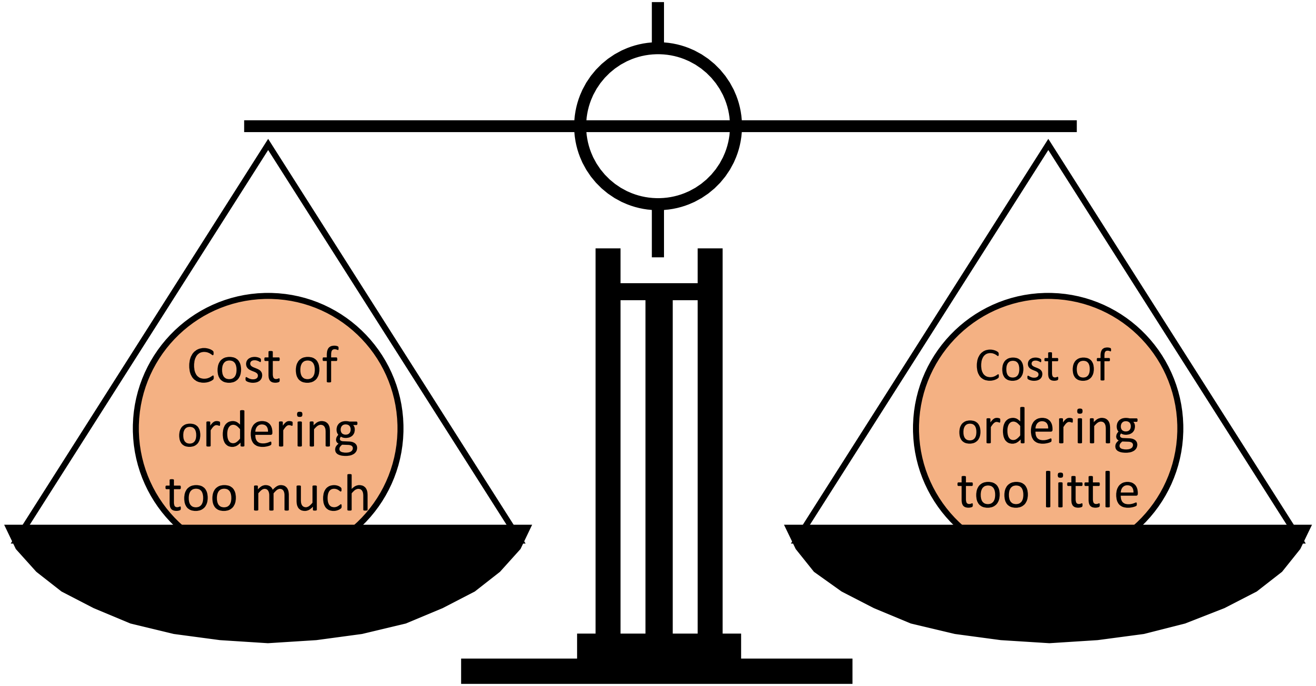
Average profit: 80.30 €/week

# Towards an Analytic Solution for Q*



# Optimal Q* by Balancing…

… the cost of ordering too much vs. cost of ordering too little



# Overage and Underage Costs

| | Mango | Papaya | |
|---|---|---|---|
| Selling price | 6.00 | 13.00 | €/unit |
| Purchase price | 3.50 | 2.50 | €/unit |
| Salvage value | 0.00 | 0.00 | €/unit |
| Salvage cost | 0.00 | 0.00 | €/unit |

Overage costs = cost of ordering too much

Question: How much does it cost to order a fruit too much?

- Answer: Purchase price + Salvage cost – Salvage value
- Mango: 3.50 + 0 – 0 = 3.50 €/unit
- Papaya: 2.50 + 0 – 0 = 2.50 €/unit

Underage costs = cost of ordering too little

Question: How much does it cost to order a fruit too little?

- Answer: Selling price - Purchase price = (lost) Profit per unit
- Mango: 6.00 – 3.50 = 2.50 €/unit
- Papaya: 13.00 – 2.50 = 10.50 €/unit

# Expected Overage Cost of $Q^{th}$ Papaya

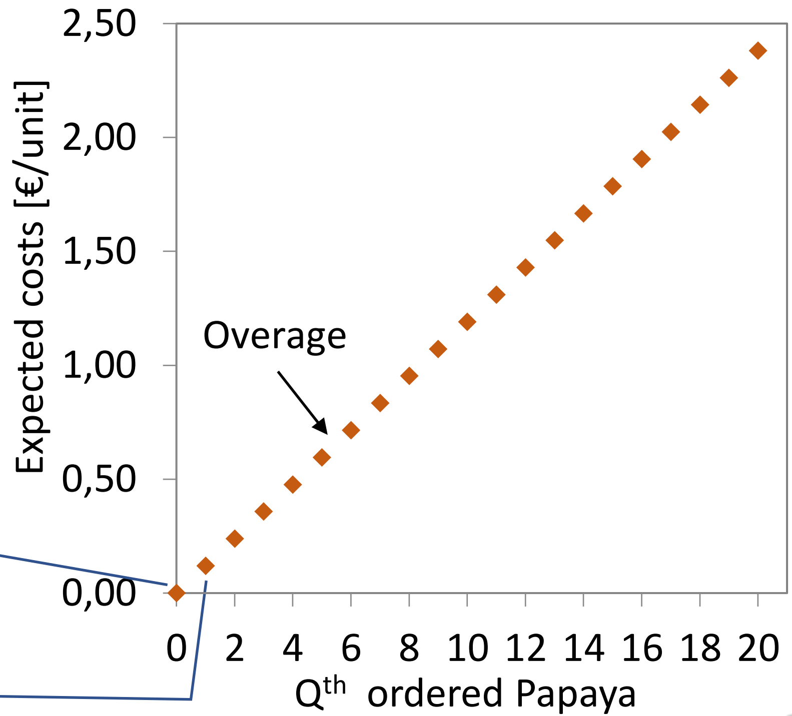


If Mr. Müller does not order any papaya at all, then none can be leftover. The expected overage costs are therefore 0 €/unit.

When Mr. Müller orders a papaya, he expects...

......that this is leftover with a probability of 1/21.

...that the leftover inventory cost is 2.50 €/unit $\cdot$ 1/21 = 0.12 €/unit.

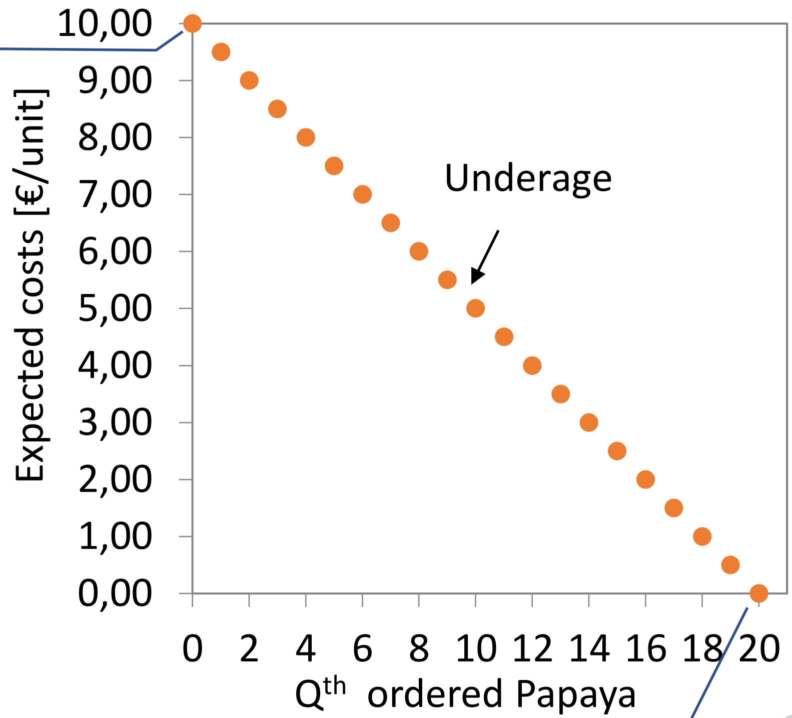


# Expected Underage costs for Q$^{th}$ Papaya

When Mr. Müller does not order any papaya, he expects ...

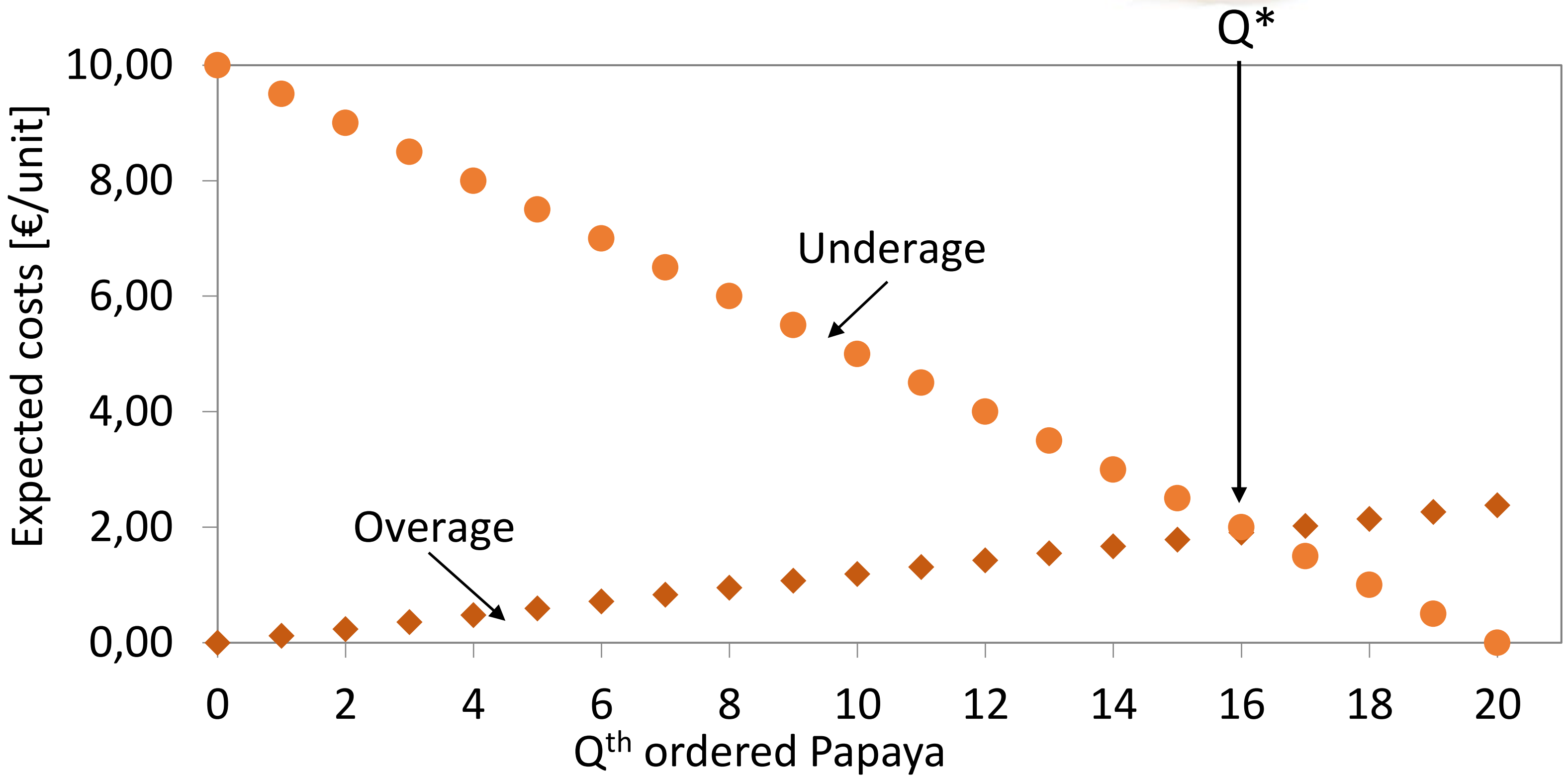
...that he could have sold one with a probability of 20/21.

... the underage costs to be
10.50 €/unit · 20/21 = 10.00 €/unit.

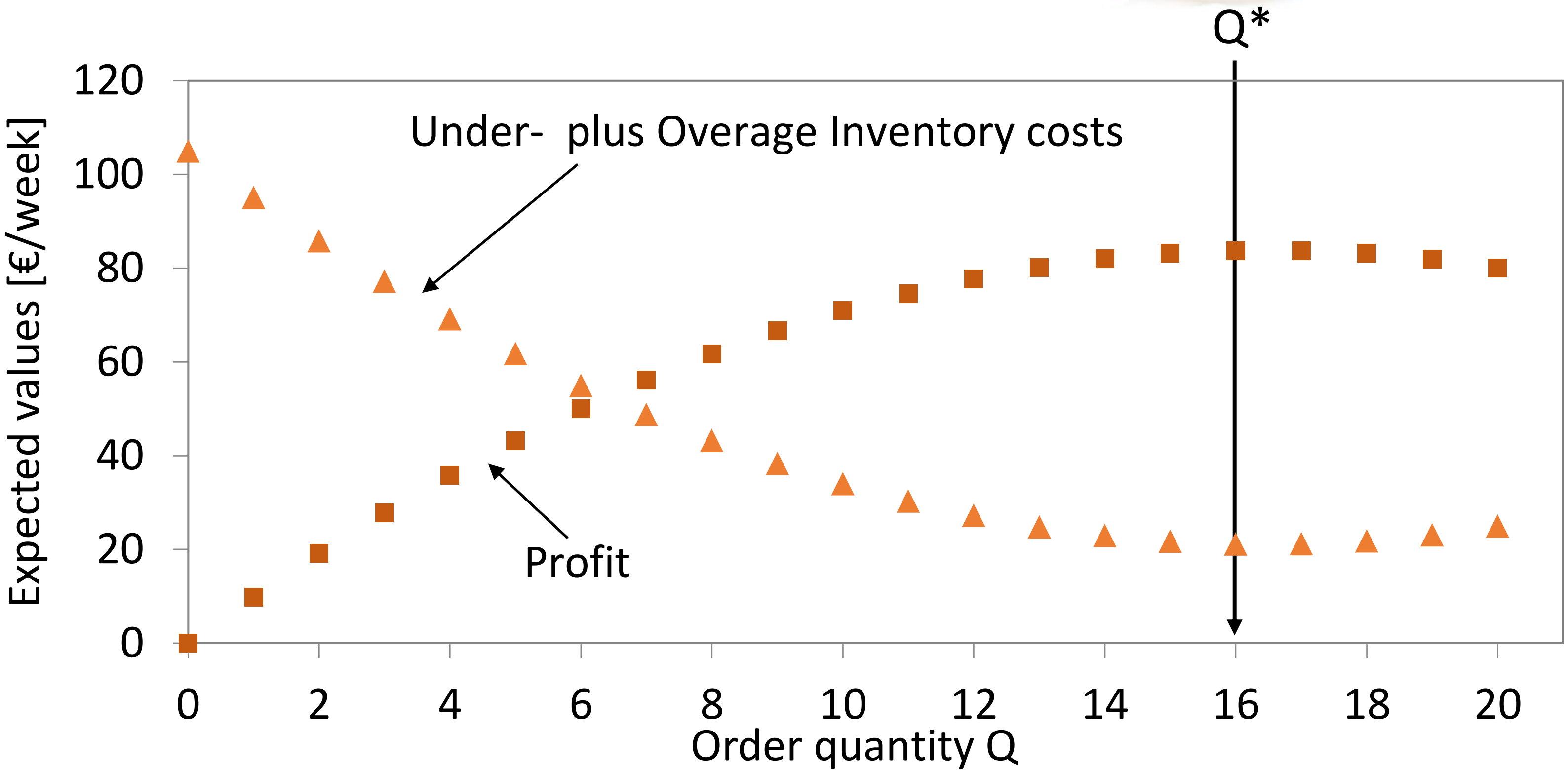



When Mr. Miller orders 20 papayas, he expects never to have too few papayas and therefore no understocking costs.

# Q* - Balance Between Expected Unit Costs



# Expected Weekly Profits as a Function of Q



# Towards a Formula for Q*: Critical Ratio

- Expected underage cost based on the $Q^{th}$ unit = $C_u \cdot (1-F(Q))$
- Expected overage cost based on the $Q^{th}$ unit = $C_o \cdot F(Q)$
- Both expected costs are in balance at:

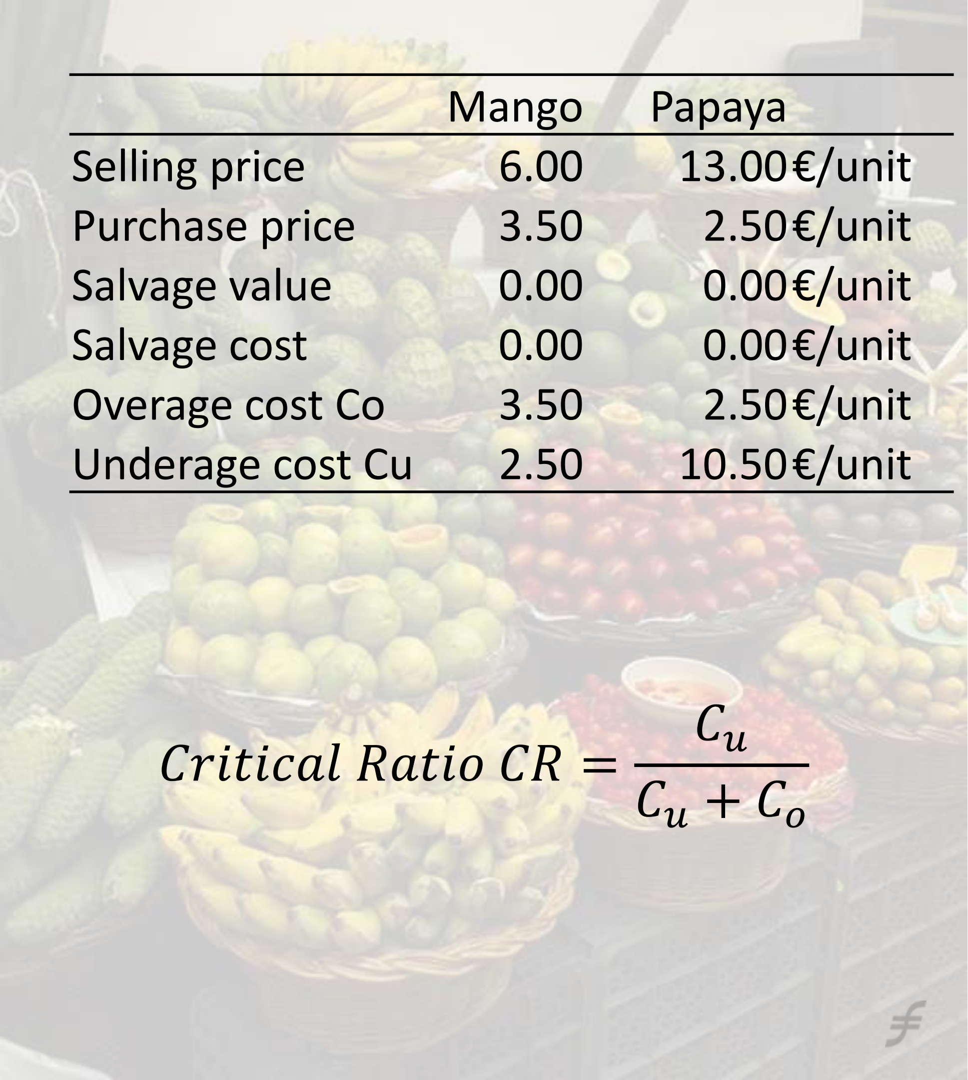
$$C_u \cdot \left(1 - F(Q)\right) = C_o \cdot F(Q)$$

- Dissolving to F(Q) gives the famous critical ratio:

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

F(Q) = Probability distribution function of demand = p{Demand ≤ Q}

# Fruchtknall Critical Ratio



| | Mango | Papaya | |
|---|---|---|---|
| Selling price | 6.00 | 13.00 | €/unit |
| Purchase price | 3.50 | 2.50 | €/unit |
| Salvage value | 0.00 | 0.00 | €/unit |
| Salvage cost | 0.00 | 0.00 | €/unit |
| Overage cost Co | 3.50 | 2.50 | €/unit |
| Underage cost Cu | 2.50 | 10.50 | €/unit |

$$Critical\ Ratio\ CR = \frac{C_u}{C_u + C_o}$$

$Optimal\ solution$:

$$p(D \leq Q^*) = CR$$

# Q* Using the Theoretical Distribution Function

- Here, the **theoretical distribution function table** for Papaya demand is used: Uniform(0, 20)
- Search the cumulated probability that is nearest but larger than the CR
- Set Q to the demand in the same line:

$$Q^{*}\text{=16 units}$$

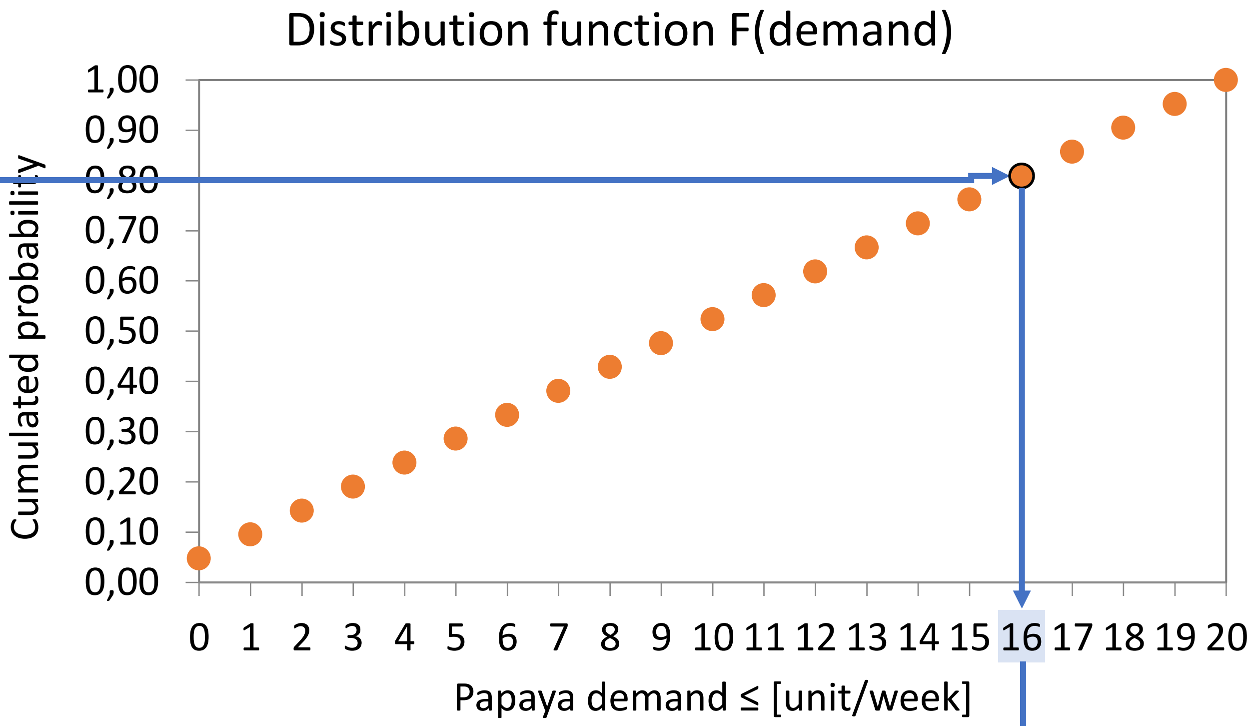
| Demand D [units/week] | Cumulated Probability F(D) |
|---|---|
| 0 | 0.04761905 |
| 1 | 0.0952381 |
| 2 | 0.14285714 |
| 3 | 0.19047619 |
| 4 | 0.23809524 |
| 5 | 0.28571429 |
| 6 | 0.33333333 |
| 7 | 0.38095238 |
| 8 | 0.42857143 |
| 9 | 0.47619048 |
| 10 | 0.52380952 |
| 11 | 0.57142857 |
| 12 | 0.61904762 |
| 13 | 0.66666667 |
| 14 | 0.71428571 |
| 15 | 0.76190476 |
| 16 | 0.80952381 |
| 17 | 0.85714286 |
| 18 | 0.9047619 |
| 19 | 0.95238095 |
| 20 | 1 |

$$CR_{Papaya} = 0.8077$$

# Obtaining Q* From a Graphical Distribution Function

$$CR_{Papaya} = 0.8077$$

$Q^*$=16 units

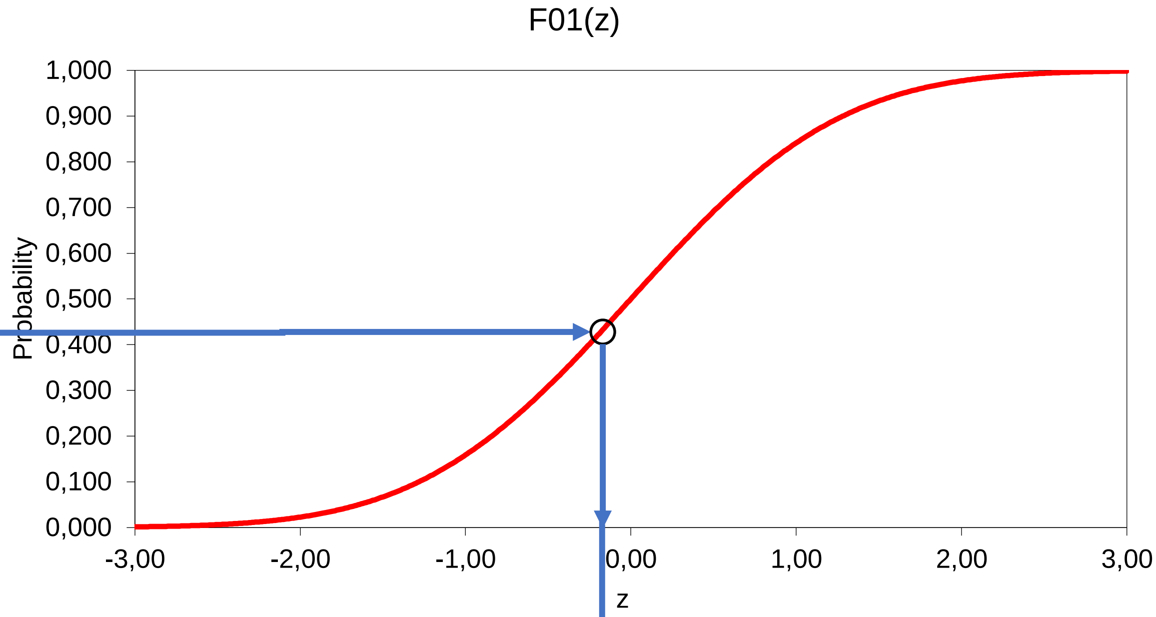


# Mango Q*: Using the Standard Normal

…distribution function to determine Q* for mangos with normally distributed demand (mean = 100 units per week, stdev = 25 units per week)

$$CR_{Mango} = 0.4167$$

$$z = -0.21$$



# Converting z to Q* for Mangos

$$z = \frac{Q - \mu}{\sigma}$$

$$Q = \mu + z \cdot \sigma$$

# Using the Standard Normal F(z)-Table

- Find the critical ratio inside the Standard Normal Distribution Function Table
- If the critical ratio falls between two values in the table, choose the greater z-statistic… this is called the round-up rule

$$z = -0.21$$

| z | Density $f_{01}(z)$ | Distribution $F_{01}(z)$ |
|---|---|---|
| -0.30 | 0.381388 | 0.382089 |
| -0.29 | 0.382515 | 0.385908 |
| -0.28 | 0.383606 | 0.389739 |
| -0.27 | 0.384663 | 0.393580 |
| -0.26 | 0.385683 | 0.397432 |
| -0.25 | 0.386668 | 0.401294 |
| -0.24 | 0.387617 | 0.405165 |
| -0.23 | 0.388529 | 0.409046 |
| -0.22 | 0.389404 | 0.412936 |
| -0.21 | 0.390242 | 0.416834 |
| -0.20 | 0.391043 | 0.420740 |
| -0.19 | 0.391806 | 0.424655 |
| -0.18 | 0.392531 | 0.428576 |
| -0.17 | 0.393219 | 0.432505 |
| -0.16 | 0.393868 | 0.436441 |
| -0.15 | 0.394479 | 0.440382 |
| -0.14 | 0.395052 | 0.444330 |
| -0.13 | 0.395585 | 0.448283 |

$$CR_{Mango} = 0.4167$$

# Conclusion

- Optimal order quantities

  For Mangos: 95 unit/Week

  For Papayas: 16 unit/Week
- Optimal order quantity almost always <> Average
- Optimal order quantity does not change from week to week

# USING A/F RATIOS TO MODEL DEMAND

# O’Neill’s Hammer 3/2 Wetsuit

- O‘Neill Inc. is a designer and manufacturer of apparel, wetsuits, and accessories
- One of their products is a wetsuit for professional surfers
- The „Hammer“ Wetsuit is produced by O‘Neill‘s contract manufacturer TEC Group in Asia



https://www.oneill.com

# O’Neill’s Hammer 3/2 Wetsuit

- TEC Group provides many benefits to O‘Neill (low cost, sourcing expertise, flexible capacity, etc.), but they have a three-month lead time on all orders
  - O‘Neill needs to order the Hammer 3/2 on Nov. 1st, to have an expected arrival of the products on Jan. 31st
  - Selling season for the Hammer 3/2: February to July
  - Leftover inventory is sold at a discounted price at the end of the season



https://www.oneill.com

# O’Neill’s Hammer 3/2 Wetsuit Economics

| | Hammer 2/3 |
|---|---|
| Selling price | 190$/unit |
| Purchase price from TEC | 110$/unit |
| Discount price* | 90$/unit |
| Salvage costs | 0$/unit |

*at end of season



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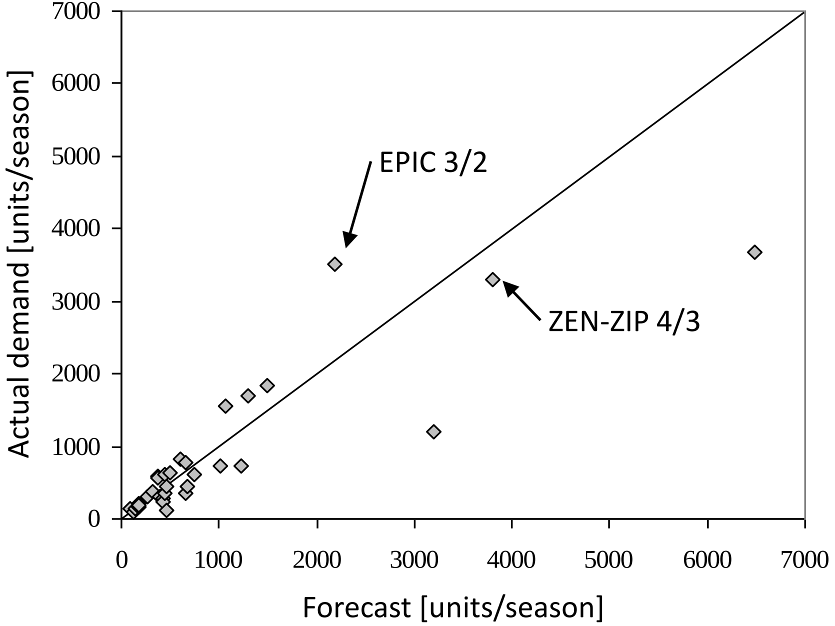
# O’Neill’s Hammer 3/2 Wetsuit Forecast

- Based on past sales data for similar products marketing and sales team forecasts 3,200 units of the Hammer 3/2 to be sold in the spring season.
- Unfortunately, the judgmental forecast is rather poor: actual demand deviates from the forecasts by more than 25% in 50% of the cases.
- The forecast becomes better over time (once the first units have been sold), but the long lead time prevents O‘Neill from later orders.

Forecasts and actual demand for surf wet-suits from the previous season



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# O’Neill’s Hammer 3/2 Wetsuit Challenges I

- How can the limited accuracy of the judgmental forecasts be considered?
- What is the optimal order quantity to be placed at TEC on 1st November?



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# A/F Ratio to Account for Forecast Errors

- Relative measure of forecast error
- Compute the A/F ratio based on past observations as:

$$A/_{F}\, ratio = \frac{Actual\ demand}{Forecast}$$

A/F ratio = 1 → perfect forecast

A/F ratio > 1 → too low forecast

A/F ratio < 1 → too high forecast

| Product description | Forecast | Actual demand [units/season] | Error* | A/F Ratio ** |
|---|---|---|---|---|
| JR ZEN FL 3/2 | 90 | 140 | -50 | 1.5556 |
| EPIC 5/3 W/HD | 120 | 83 | 37 | 0.6917 |
| JR ZEN 3/2 | 140 | 143 | -3 | 1.0214 |
| WMS ZEN-ZIP 4/3 | 170 | 163 | 7 | 0.9588 |
| HEATWAVE 3/2 | 170 | 212 | -42 | 1.2471 |
| JR EPIC 3/2 | 180 | 175 | 5 | 0.9722 |
| WMS ZEN 3/2 | 180 | 195 | -15 | 1.0833 |
| ZEN-ZIP 5/4/3 W/HOOD | 270 | 317 | -47 | 1.1741 |
| WMS EPIC 5/3 W/HD | 320 | 369 | -49 | 1.1531 |
| EVO 3/2 | 380 | 587 | -207 | 1.5447 |
| JR EPIC 4/3 | 380 | 571 | -191 | 1.5026 |
| WMS EPIC 2MM FULL | 390 | 311 | 79 | 0.7974 |
| HEATWAVE 4/3 | 430 | 274 | 156 | 0.6372 |
| ZEN 4/3 | 430 | 239 | 191 | 0.5558 |
| EVO 4/3 | 440 | 623 | -183 | 1.4159 |
| ZENFL 3/2 | 450 | 365 | 85 | 0.8111 |
| HEAT 4/3 | 460 | 450 | 10 | 0.9783 |
| ZEN-ZIP 2MM FULL | 470 | 116 | 354 | 0.2468 |
| HEAT 3/2 | 500 | 635 | -135 | 1.2700 |
| WMS EPIC 3/2 | 610 | 830 | -220 | 1.3607 |
| WMS ELITE 3/2 | 650 | 364 | 286 | 0.5600 |
| ZEN-ZIP 3/2 | 660 | 788 | -128 | 1.1939 |
| ZEN 2MM S/S FULL | 680 | 453 | 227 | 0.6662 |
| EPIC 2MM S/S FULL | 740 | 607 | 133 | 0.8203 |
| EPIC 4/3 | 1020 | 732 | 288 | 0.7176 |
| WMS EPI 4/3 | 1060 | 1552 | -492 | 1.4642 |
| JR HAMMER 3/2 | 1220 | 721 | 499 | 0.5910 |
| HAMMER 3/2 | 1300 | 1696 | -396 | 1.3046 |
| HAMMER S/S FULL | 1490 | 1832 | -342 | 1.2295 |
| EPIC 3/2 | 2190 | 3504 | -1314 | 1.6000 |
| ZEN 3/2 | 3190 | 1195 | 1995 | 0.3746 |
| ZEN-ZIP 4/3 | 3810 | 3289 | 521 | 0.8633 |
| WMS HAMMER 3/2 FULL | 6490 | 3673 | 2817 | 0.5659 |

*Error = Forecast - Actual Demand

** A/F Ratio = Actual Demand divided by Forecast

# A/F-based Forecasting

Schritt 1: Estimate the distribution of the A/F ratios determined From the data using statistical software (e.g., Kolmogorov- Smirnov Or Anderson-Darling test)

→ Normal distribution hypothesis is not rejected

Step 2: Determination of the normal distribution parameters

$\mu = 0.9975$

$\sigma = 0.3690$

| Product description | Forecast | Actual demand [units/season] | Error | A/F Ratio |
|---|---|---|---|---|
| JR ZEN FL 3/2 | 90 | 140 | -50 | 1.5556 |
| EPIC 5/3 W/HD | 120 | 83 | 37 | 0.6917 |
| JR ZEN 3/2 | 140 | 143 | -3 | 1.0214 |
| … | … | … | … | … |
| ZEN 3/2 | 3190 | 1195 | 1995 | 0.3746 |
| ZEN-ZIP 4/3 | 3810 | 3289 | 521 | 0.8633 |
| WMS HAMMER 3/2 FULL | 6490 | 3673 | 2817 | 0.5659 |
| Average | 941.82 | 824.36 | 117.45 | 0.9978 |
| Standard deviation | 1283.56 | 949.73 | 671.12 | 0.3638 |

# Using Historical A/F Ratios to Model Demand

- Judgmental forecast for the Hammer 3/2: 3,200 units per season
- Determine a normally distributed demand model:

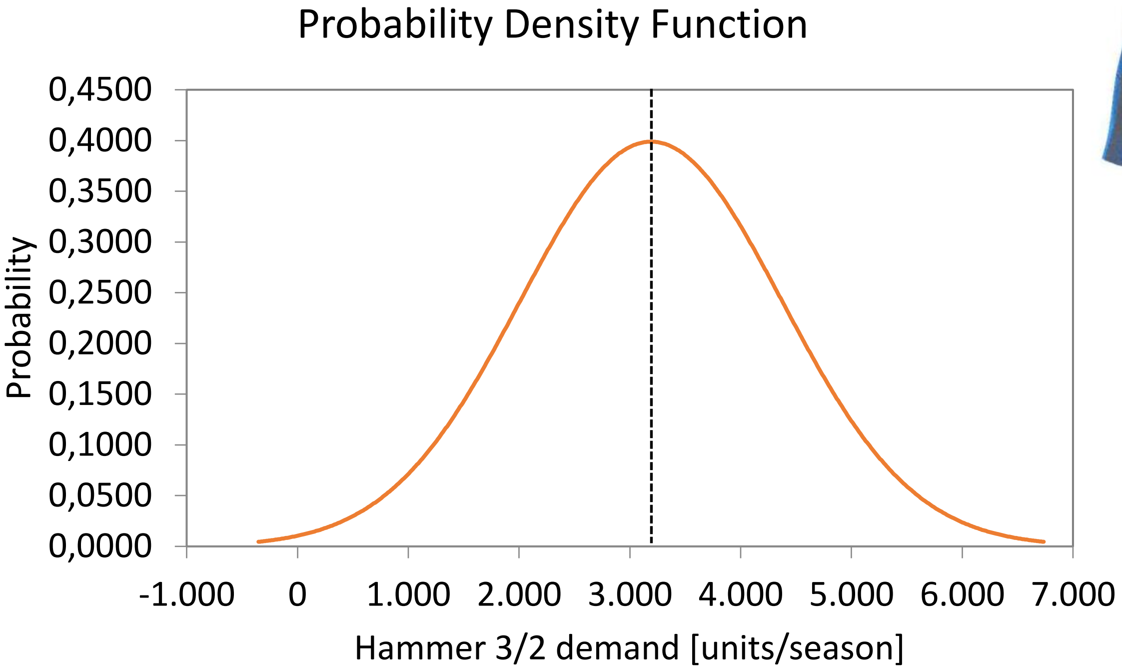
$$\mu_{\substack{Demand \\ Hammer\ 3/2}} = 0.9975 \cdot 3{,}200 \frac{units}{season} = 3{,}192 \frac{units}{season}$$

$$\sigma_{\substack{Demand \\ Hammer\ 3/2}} = 0.3690 \cdot 3{,}200 \frac{units}{season} = 1{,}181 \frac{units}{season}$$

$$\mu_{Demand} = \mu_{AF} \cdot \begin{matrix} Judgemental \\ forecast \end{matrix}$$

$$\sigma_{Demand} = \sigma_{AF} \cdot \begin{matrix} Judgemental \\ forecast \end{matrix}$$

# O'Neill's Hammer 3/2 Wetsuit Demand Model



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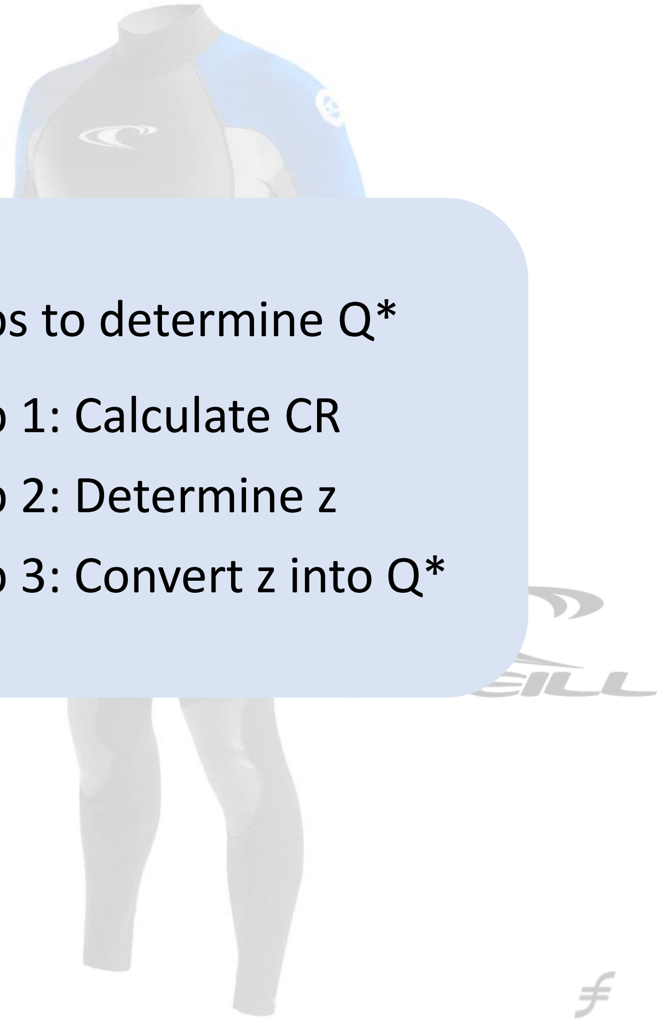
# O’Neill’s Hammer 3/2 Wetsuit Challenges I

- How can the limited accuracy of the judgmental forecasts be considered?
- **What is the optimal order quantity to be placed at TEC on 1st November?**



Steps to determine Q*

Step 1: Calculate CR

Step 2: Determine z

Step 3: Convert z into Q*



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# Hammer 3/2 Critical Ratio

Step 1: Determine CR

$$CR_{Hammer\ 3/2} =$$

| | Hammer 2/3 |
|---|---|
| Selling price | 190 $/unit |
| Purchase price from TEC | 110 $/unit |
| Discount price* | 90 $/unit |
| Salvage costs | 0 $/unit |

*at end of season

$$Critical\ Ratio\ CR = \frac{C_u}{C_u + C_o}$$



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# Optimal Order Quantity Q* Hammer 3/2

Step 2: Determine Q such that there is a probability (Demand $\leq$ Q) = CR

Step 2a: Determine z

Methode 1: Statistical Table method

| z | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 |
|---|---|---|---|---|---|---|---|---|---|---|
| **0.0** | 0.5000 | 0.5040 | 0.5080 | 0.5120 | 0.5160 | 0.5199 | 0.5239 | 0.5279 | 0.5319 | 0.5359 |
| **0.1** | 0.5398 | 0.5438 | 0.5478 | 0.5517 | 0.5557 | 0.5596 | 0.5636 | 0.5675 | 0.5714 | 0.5753 |
| **0.2** | 0.5793 | 0.5832 | 0.5871 | 0.5910 | 0.5948 | 0.5987 | 0.6026 | 0.6064 | 0.6103 | 0.6141 |
| **0.3** | 0.6179 | 0.6217 | 0.6255 | 0.6293 | 0.6331 | 0.6368 | 0.6406 | 0.6443 | 0.6480 | 0.6517 |
| **0.4** | 0.6554 | 0.6591 | 0.6628 | 0.6664 | 0.6700 | 0.6736 | 0.6772 | 0.6808 | 0.6844 | 0.6879 |
| **0.5** | 0.6915 | 0.6950 | 0.6985 | 0.7019 | 0.7054 | 0.7088 | 0.7123 | 0.7157 | 0.7190 | 0.7224 |
| **0.6** | 0.7257 | 0.7291 | 0.7324 | 0.7357 | 0.7389 | 0.7422 | 0.7454 | 0.7486 | 0.7517 | 0.7549 |
| **0.7** | 0.7580 | 0.7611 | 0.7642 | 0.7673 | 0.7704 | 0.7734 | 0.7764 | 0.7794 | 0.7823 | 0.7852 |
| **0.8** | 0.7881 | 0.7910 | 0.7939 | 0.7967 | 0.7995 | 0.8023 | 0.8051 | 0.8078 | 0.8106 | 0.8133 |
| **0.9** | 0.8159 | 0.8186 | 0.8212 | 0.8238 | 0.8264 | 0.8289 | 0.8315 | 0.8340 | 0.8365 | 0.8389 |
| **1.0** | 0.8413 | 0.8438 | 0.8461 | 0.8485 | 0.8508 | 0.8531 | 0.8554 | 0.8577 | 0.8599 | 0.8621 |

Methode 2: Computer method

For example, in Excel use:

z = NORM.S.INV(CR)

Step 2b: Covert z into Q*

# NEWSVENDOR PERFORMANCE MEASURES

# O’Neill’s Hammer 3/2 Wetsuit Challenges II

If O’Neill orders 4,000 Hammer 3/2 wetsuits…

- …what is expected inventory?
- …what is expected sales (expected lost sales)?
- …what is expected profit?
- …what is the in-stock probability?
- …what is the stockout probability?



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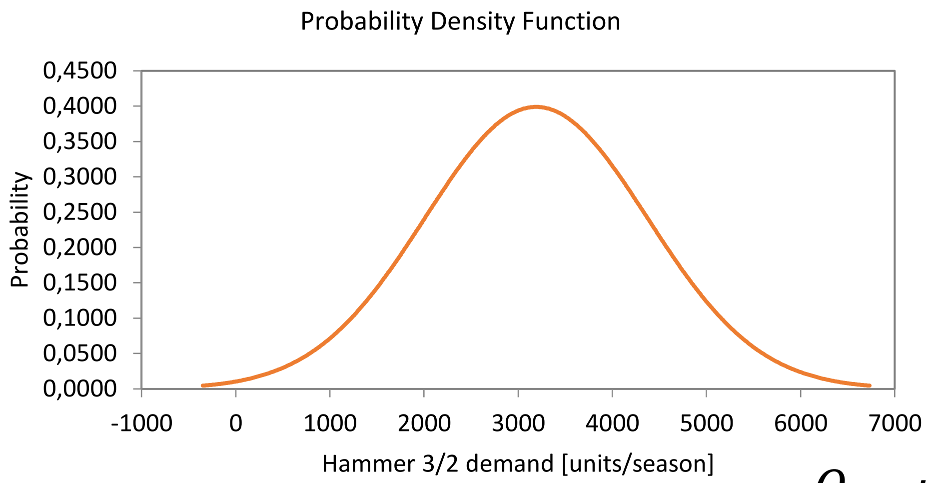
# Converting Q to the Standard Normal z

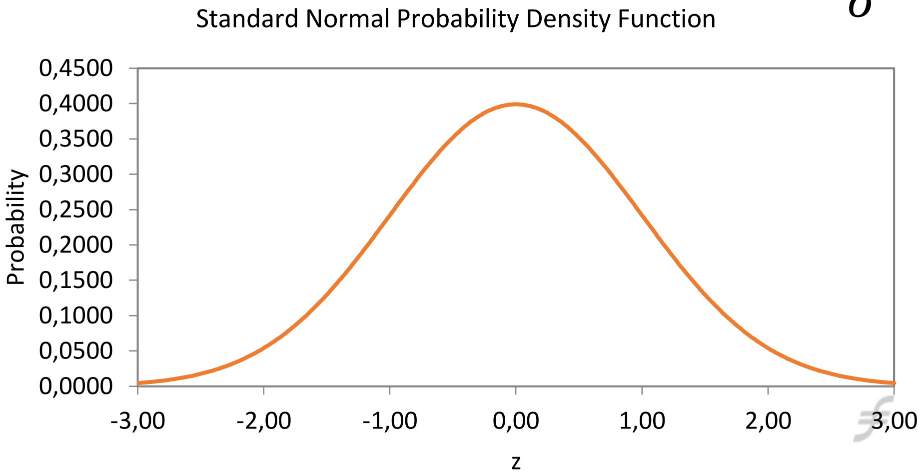
$$Q = 4{,}000\ \frac{units}{season}$$

$$z = \frac{4{,}000\ \frac{units}{season} - 3{,}192\ \frac{units}{season}}{1{,}181\ \frac{units}{season}}$$

$$z = 0.6842$$




$$z = \frac{Q - \mu}{\sigma}$$



# Expected Inventory

$z = 0.6842$

**Standard Normal Inventory Function Table, I(z)**

| z | 0 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 |
|---|---|---|---|---|---|---|---|---|---|---|
| **0.0** | 0.3989 | 0.4040 | 0.4090 | 0.4141 | 0.4193 | 0.4244 | 0.4297 | 0.4349 | 0.4402 | 0.4456 |
| **0.1** | 0.4509 | 0.4564 | 0.4618 | 0.4673 | 0.4728 | 0.4784 | 0.4840 | 0.4897 | 0.4954 | 0.5011 |
| **0.2** | 0.5069 | 0.5127 | 0.5186 | 0.5244 | 0.5304 | 0.5363 | 0.5424 | 0.5484 | 0.5545 | 0.5606 |
| **0.3** | 0.5668 | 0.5730 | 0.5792 | 0.5855 | 0.5918 | 0.5981 | 0.6045 | 0.6109 | 0.6174 | 0.6239 |
| **0.4** | 0.6304 | 0.6370 | 0.6436 | 0.6503 | 0.6569 | 0.6637 | 0.6704 | 0.6772 | 0.6840 | 0.6909 |
| **0.5** | 0.6978 | 0.7047 | 0.7117 | 0.7187 | 0.7257 | 0.7328 | 0.7399 | 0.7471 | 0.7542 | 0.7614 |
| **0.6** | 0.7687 | 0.7759 | 0.7833 | 0.7906 | 0.7980 | 0.8054 | 0.8128 | 0.8203 | 0.8278 | 0.8353 |
| **0.7** | 0.8429 | 0.8505 | 0.8581 | 0.8658 | 0.8734 | 0.8812 | 0.8889 | 0.8967 | 0.9045 | 0.9123 |
| **0.8** | 0.9202 | 0.9281 | 0.9360 | 0.9440 | 0.9520 | 0.9600 | 0.9680 | 0.9761 | 0.9842 | 0.9923 |
| **0.9** | 1.0004 | 1.0086 | 1.0168 | 1.0250 | 1.0333 | 1.0416 | 1.0499 | 1.0582 | 1.0665 | 1.0749 |
| **1.0** | 1.0833 | 1.0917 | 1.1002 | 1.1087 | 1.1172 | 1.1257 | 1.1342 | 1.1428 | 1.1514 | 1.1600 |

$I(0.69) = 0.8353$

$$Expected\ inventory = 1{,}181 \cdot 0.8353$$
$$= 986.50$$

- Expected inventory: expected number of units left over at the end of the selling period (before salvaging).
- Intuition: The more we order the higher is the chance that demand is lower than our order and the higher is inventory.

$$Expected\ inventory = \sigma \cdot I(z)$$

# Expected Sales

$$Expected\ Sales$$

$$= 4000\,\frac{units}{season} - 986.50\,\frac{units}{season}$$

$$= 3{,}013.50\ \frac{units}{season}$$

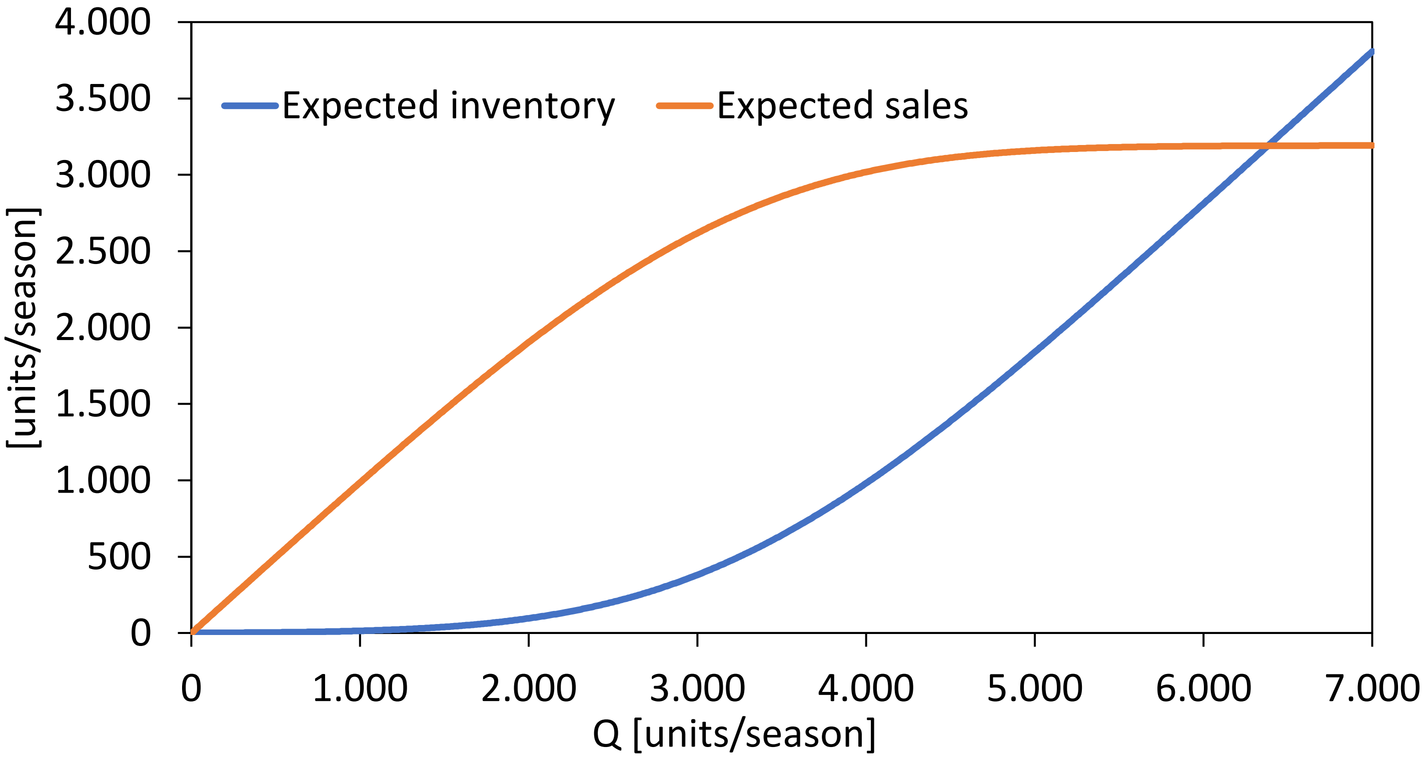
- Expected sales: expected number of units sold in the selling period (before salvaging).
- Intuition: The more we order the lower is the chance that demand is higher than Q.

$$Sales + Inventory = Q$$

$$\begin{matrix} Expected \\ sales \end{matrix} + \begin{matrix} Expected \\ inventory \end{matrix} = Q$$

$$\begin{matrix} Expected \\ sales \end{matrix} = Q - \begin{matrix} Expected \\ inventory \end{matrix}$$

# Expected Inventory and Sales as a Function of Q

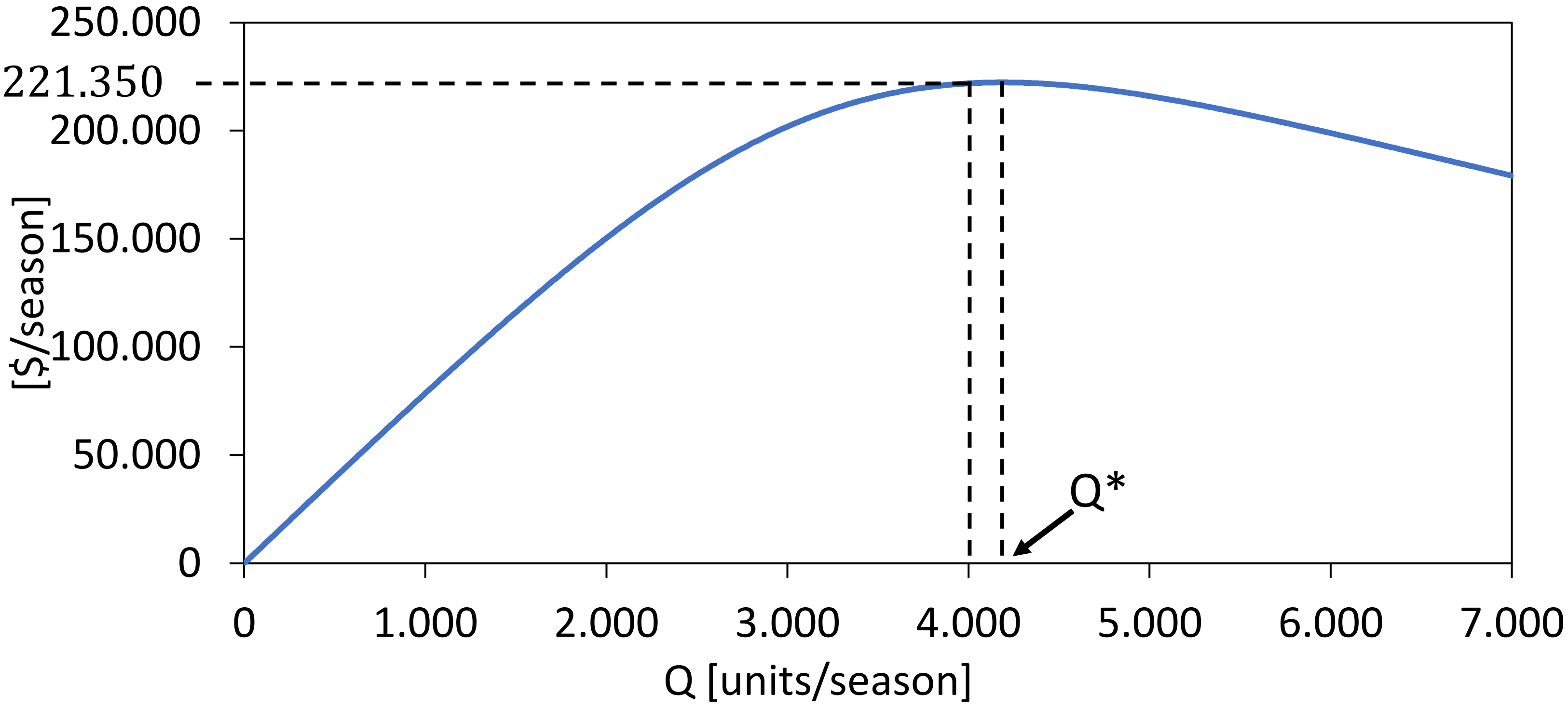


# Expected Profit

$$\begin{aligned}\begin{matrix}\textit{Expected}\\ \textit{profit}\end{matrix} &= 190\ \frac{\$}{unit}\cdot 3{,}013.50\,\frac{units}{season}\\ &+ 90\ \frac{\$}{unit}\cdot 986.50\,\frac{units}{season}\\ &- 110\ \frac{\$}{unit}\cdot 4{,}000\,\frac{units}{season}\\ &= 221{,}350\ \frac{\$}{season}\end{aligned}$$

$$\begin{aligned}\begin{matrix}\textit{Expected}\\ \textit{profit}\end{matrix} &= \begin{matrix}\textit{Selling}\\ \textit{price}\end{matrix}\cdot\begin{matrix}\textit{Expected}\\ \textit{sales}\end{matrix}\\ &+ \begin{matrix}\textit{Discount}\\ \textit{price}\end{matrix}\cdot\begin{matrix}\textit{Expected}\\ \textit{inventory}\end{matrix}\\ &- \begin{matrix}\textit{Purchase}\\ \textit{price}\end{matrix}\cdot Q\end{aligned}$$

# Expected Profit as a Function of Q



# In-stock Probability

$$Q = 4{,}000\ \frac{units}{season}$$

$$z = \frac{4{,}000\,\frac{units}{season} - 3{,}192\,\frac{units}{season}}{1{,}181\,\frac{units}{season}}$$

$$z = 0.6842$$

Using the standard normal distribution function table:

$$In\text{-}stock\ probability = F(0.6842) = 0.7549$$

- In-stock probability: probability all demand is satisfied
- All demand is satisfied if demand is the order quantity, Q, or smaller
- The distribution function tells us the probability that demand is Q or smaller!

$$In\text{-}stock\ probability = F(Q)$$

# Stockout Probability

$$Q = 4{,}000\ \frac{units}{season}$$

$$z = \frac{4{,}000\,\frac{units}{season} - 3{,}192\,\frac{units}{season}}{1{,}181\,\frac{units}{season}}$$

$$z = 0.6842$$

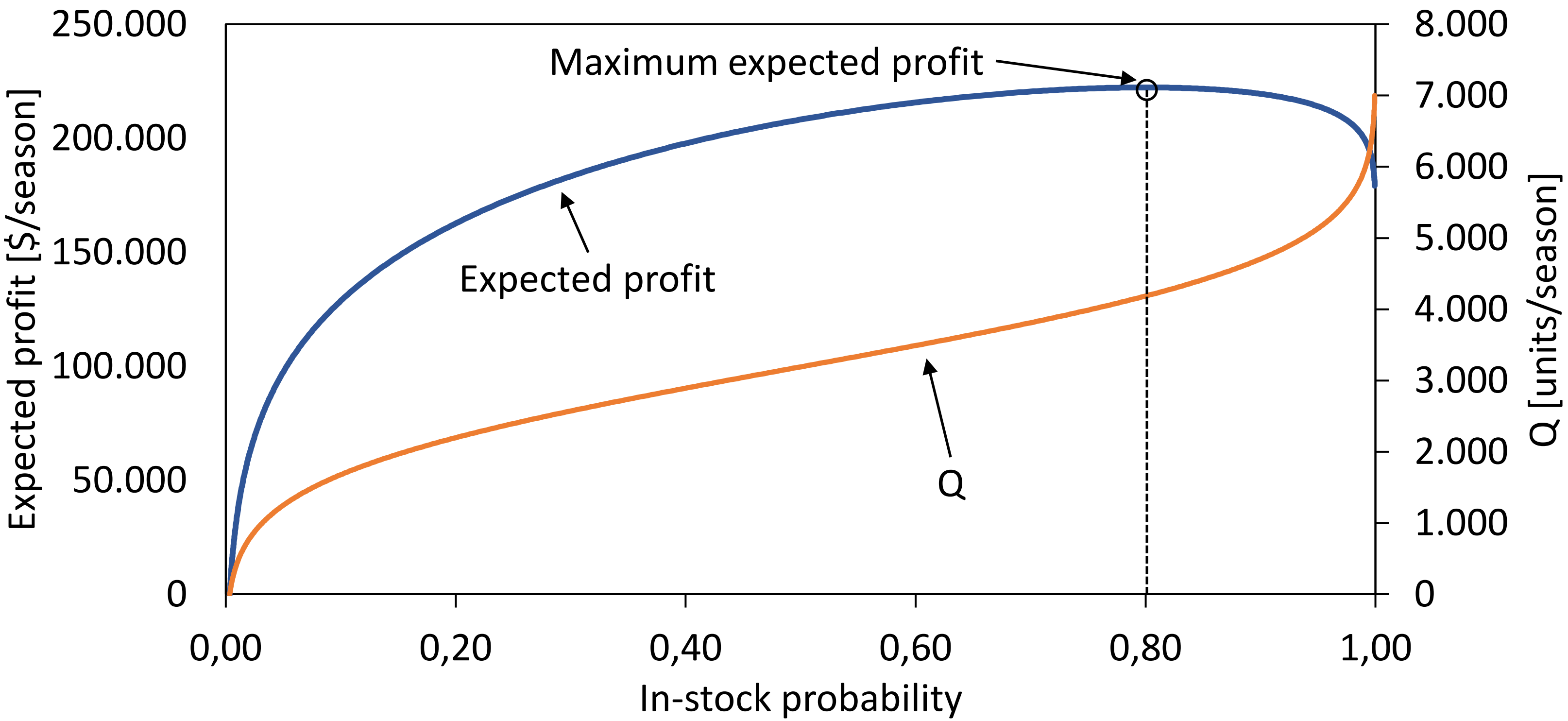
Using the standard normal distribution function table

$$Stockout\ probability = 1 - F(0.6842)$$
$$= 1 - 0.7549 = 0.2451$$

- Stockout probability: probability that some demand is **not** satisfied
- Some demand is not satisfied if demand exceeds the order quantity, Q
- Thus

$$Stockout\ probability$$
$$= 1 - F(Q)$$
$$= 1 - \begin{matrix} In\text{-}stock \\ probability \end{matrix}$$

# Expected Profit and In-stock Probability Trade-off



# O'Neill's Hammer 3/2 Wetsuit Challenge III

- How many Hammer 3/2 should O'Neill order to guarantee an in-stock probability of 99%?



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# Choose Q to Achieve 99% In-stock Probability

In the Standard Normal Distribution Function Table, we find:

$$F(2.32) = 0.9898$$
$$F(2.33) = 0.9901$$

Choose z = 2.33 to satisfy the 99% in-stock probability constraint

$$Q = 3{,}192 \frac{units}{season} + 2.33 \cdot 1{,}181 \frac{units}{season}$$

$$Q = 5{,}944 \frac{units}{season}$$

- Step 1:

  Find the z-statistic that yields the target in-stock probability

- Step 2:

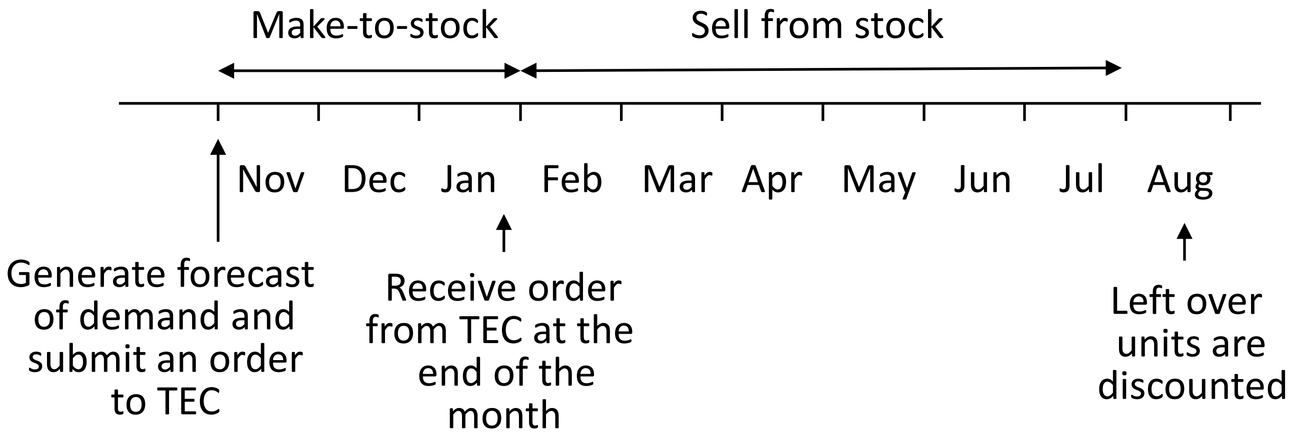
  Convert the z-statistic into an order quantity for the actual demand distribution

$$Q = \mu + z \cdot \sigma$$

# MISMATCH COSTS IN THE NEWSVENDOR MODEL

# The Newsvendor Dilemma

- "Newsvendors" can manage, but not avoid, the dilemma:
  - Order too much → inventory is left over at the end of the selling period
  - Order too little → opportunity cost of lost sales
- Dilemma arises because the newsvendor commits to its entire supply before demand occurs: Make-to-Stock system




# Maximum Profit

- Maximum profit (=highest possible expected profit) is used as benchmark.
- The maximum profit is the profit without any mismatch costs, i.e., every unit is sold and there are no lost sales:

$$Maximum\ profit = Expected\ demand\ \mu \cdot (Selling\ price\ - Purchase\ price)$$

$$Maximum\ profit = 3{,}192\,\frac{units}{season} \cdot (190 - 110)\,\frac{\$}{unit} = 255{,}360\,\frac{\$}{season}$$

- Maximum profit depends only on two factors: expected demand and profit per unit sold.

# The Demand-Supply Mismatch Costs

- Maximum profit does not suffer from the two types of mismatch costs:
  - Cost of inventory (because of ordering too much)
  - Opportunity cost of stockouts (because of ordering too little)
- Expected profit suffers from mismatch costs, thus:

$$Expected\ profit = Maximum\ profit - Mismatch\ costs$$

- Rearranging for mismatch costs yields:

$$Mismatch\ costs = Maximum\ profit - Expected\ profit$$

# Expected Profit for Hammer 3/2 Q*

$$\mu_{\substack{Demand \\ Hammer\ 3/2}} = 3{,}192 \frac{units}{season}$$

$$\sigma_{\substack{Demand \\ Hammer\ 3/2}} = 1{,}181 \frac{units}{season}$$

$$Q^* = 4{,}196 \frac{units}{season}$$

$$Selling\ price = 190 \frac{\$}{unit}$$

$$Purchase\ price = 110 \frac{\$}{unit}$$

$$Discount\ price = 90 \frac{\$}{unit}$$

# Hammer 3/2 Mismatch Costs

- For the Hammer 3/2, mismatch cost are
  $255,360 - $222,307 = $33,053 per season.
- Alternative way to determine mismatch costs:

$$Mismatch\ costs = c_u(\mu - expected\ sales) + c_o \cdot expected\ inventory$$
$$= c_u \cdot expected\ lost\ sales + c_o \cdot expected\ inventory$$

$$Mismatch\ costs = 80\frac{\$}{unit}(3{,}192 - 3{,}062.27)\frac{unit}{season}$$
$$+20\frac{\$}{unit} \cdot 1{,}133.73\frac{unit}{season} = 33{,}053\frac{\$}{season}$$

# Significance of Mismatch Costs

- Hammer 3/2 mismatch costs $33,053 per season account for:

$$\frac{33{,}053\,\frac{\$}{season}}{222{,}307.34\,\frac{\$}{season}} = 14.87\%$$ of expected profits

$$\frac{33{,}053\,\frac{\$}{season}}{683{,}867.34\,\frac{\$}{season}} = 4.83\%$$ of expected revenues

- Typical net profit in the apparel industry: 2% to 5% of revenue

→ Mismatch costs are significant

# Factors Impacting Mismatch Costs

Mismatch costs depend on:

- Demand variability (measured as the coefficient of variation)

  AND

- $Critical\ ratio = \dfrac{C_u}{C_o + C_u}$

What do you think?

- If demand variability increases, what happens to mismatch costs?
- If the critical ratio increases, what happens to mismatch costs?

# Mismatch Cost…

… as percentage of the maximum profit

| Coefficient of variation | Critical ratio 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|---|---|---|---|---|---|---|
| 0.10 | 10% | 8% | 6% | 5% | 3% | 2% |
| 0.25 | 24% | 20% | 16% | 12% | 9% | 5% |
| 0.40 | 39% | 32% | 26% | 20% | 14% | 8% |
| 0.55 | 53% | 44% | 35% | 27% | 19% | 11% |
| 0.70 | 68% | 56% | 45% | 35% | 24% | 14% |
| 0.85 | 82% | 68% | 55% | 42% | 30% | 17% |
| 1.00 | 97% | 80% | 64% | 50% | 35% | 19% |

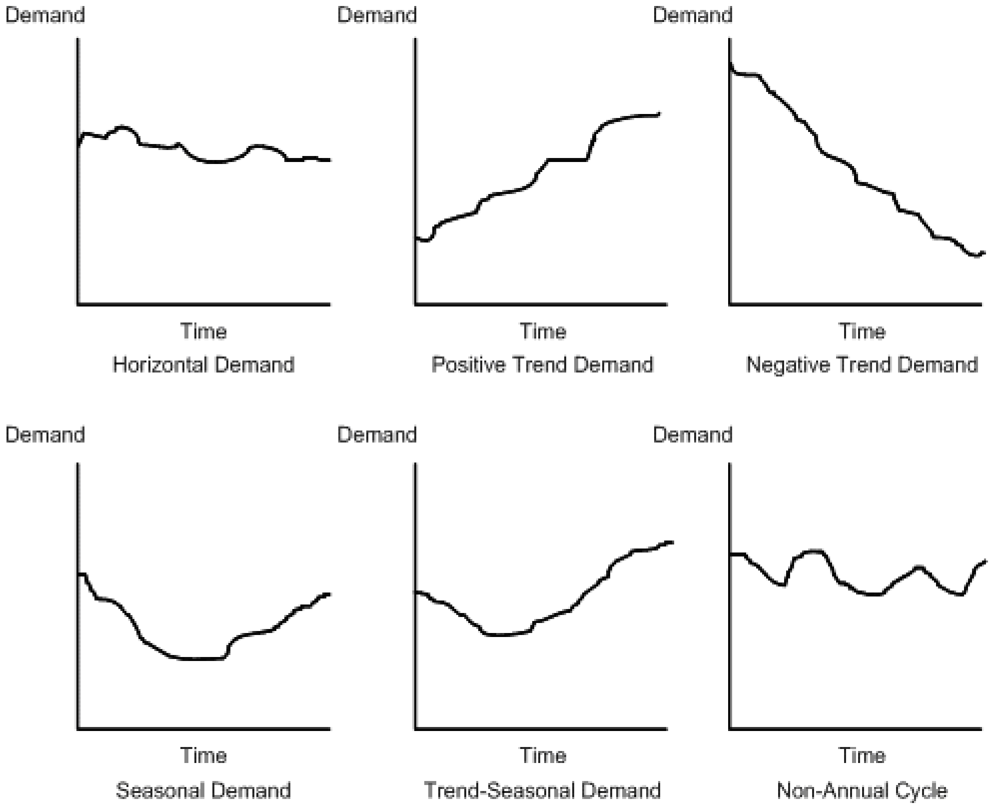
# STRATEGIES TO MANAGE A NEWSVENDOR SYSTEM

# Strategies for the Newsvendor

- Do not sell the product
- Increase the profit margin, thus increase the critical ratio
- Reduce demand uncertainty (improve forecasting, product pooling)
- Quick response: order or produce late in the season
- Make-to-order

# Improve Demand Forecasting

- Many improvement options, e.g.
  - Analyze demand patterns and use the most adequate forecasting technique
  - Track forecasting accuracy and learn from errors
  - …
- Limit to this strategy: most forecasts are still wrong



# Demand Pooling

- Reduce the variety offered to customers by combining, or pooling, similar products
- Using statistical economies of scale: aggregating demand into a large scale tends to reduce uncertainty (coefficient of variation ↓).

Impact of demand pooling of two products with identical demand distribution:

Expected pooled demand:

$$\mu_{pooled} = 2 \cdot \mu$$

Standard deviation pooled demand:

$$\sigma_{pooled} = \sqrt{2(1 + Correlation)} \cdot \sigma$$

# Hammer 3/2 Demand Pooling

$$\mu_{pooled} = 2 \cdot 3{,}192 = 6{,}384 \frac{units}{season}$$

$$\sigma_{pooled} = \sqrt{2(1+0)} \cdot 1{,}181 \frac{units}{season}$$

$$= 1{,}670.19 \frac{units}{season}$$

$$CV = \frac{1{,}670.19}{6{,}384} = 0.2616$$

Selling the Hammer 3/2 to two customer segments with identically distributed, uncorrelated demand:

Surfing

Scuba diving

$$\mu = 3{,}192 \frac{units}{season} \qquad \mu = 3{,}192 \frac{units}{season}$$

$$\sigma = 1{,}181 \frac{units}{season} \qquad \sigma = 1{,}181 \frac{units}{season}$$

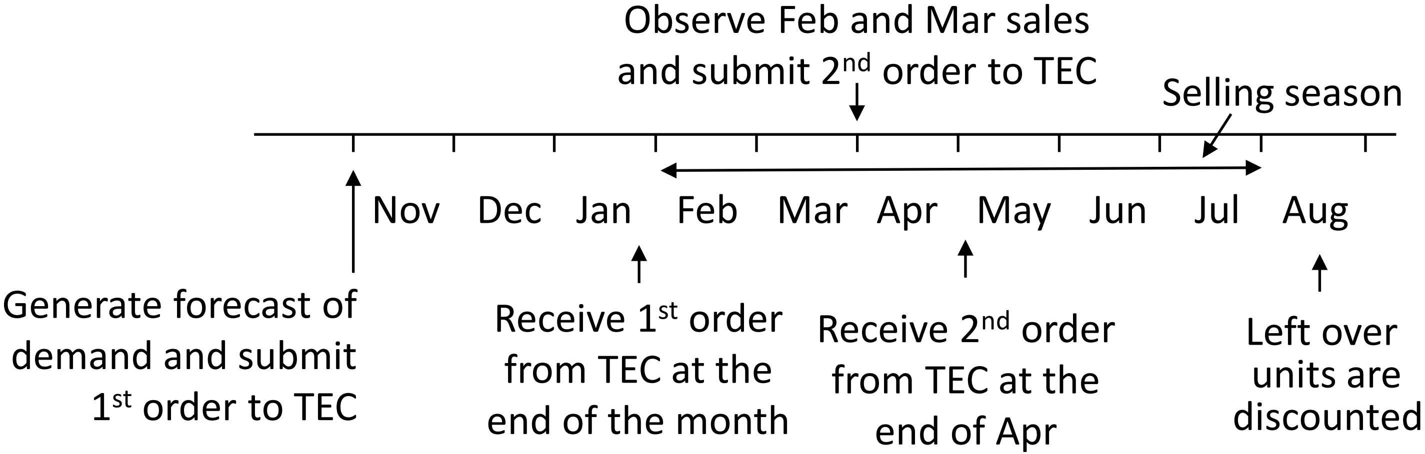
$$CV = \frac{1{,}181}{3{,}192} = 0.3700$$

# Quick Response

- Capability to respond to updated demand information, e.g. by using reactive capacity
- Reactive capacity allows the firm to react to changes in its demand forecast
- Examples of reactive capacity
  - Spare capacity
  - Flexible suppliers

# Quick Response with Reactive Capacity at O’Neill

- TEC allows O’Neill to place a second order with fast 4-week delivery.
- TEC charges a premium of 20 % per unit ($132 vs. $110) in the second order.
- There are no restrictions imposed on the 2nd order quantity.
- O’Neill’s updated forecast of total season sales is (nearly) perfect end of March.




# Impact of O'Neill's 2nd Order Option on the CR

- One order only
- Economics
  - Selling price: 190 \$/unit
  - Purchase price: 110 \$/unit
  - Discount price: 90 \$/unit

$$Critical\ Ratio\ CR = \frac{(190-110)}{(190-110)+(110-90)} = 0.8$$

- 1st order 1st November, 2nd order 31st March if updated demand forecast higher than Q of first order
- Purchase price 2nd order: 132 \$/unit
- Overage cost do not change
- Underage cost:
  132 – 110 = 22 \$/unit

$$Critical\ Ratio\ CR = \frac{(132-110)}{(132-110)+(110-90)} = 0.5238$$

# Impact of O'Neill's 2nd Order Option on the Exp. Profit

| | No quick response | Quick response | |
|---|---|---|---|
| Q* first order | 4,196 | 3,263 | units/season |
| Expected Q second order | - | 436.43 | units/season |
| Expected inventory | 1,133.73 | 507.43 | units/season |
| Expected sales | 3,062.27 | 2,755.57 | units/season |
| Expected lost sales | 129.73 | 0.00 | units/season |
| Maximum profit | 255,360.00 | 255,360 | $/season |
| Expected profit | 222,307 | 235,610 | $/season |
| Mismatch costs | 33,053 | 19,750 | $/season |

# Make-to-Order

- An item's production begins after the customer for the item is known.
- Units are generally delivered to a customer immediately after production is completed, thereby not spending time in inventory.
- Opposite of make-to-stock

# Make-to-Order Pros and Cons

| Make-to-Order | |
|---|---|
| **Advantages** | **Disadvantages** |
| ▪ No leftover (finished-goods) inventory<br>▪ No lost sales<br>▪ Mismatch costs can be entirely eliminated<br>→ Particularly firms with high CVs and low critical ratios benefit from switching to Make-to-Order. | ▪ Customers must wait for order to be fulfilled (willingness depends on products) → queuing system with potentially high wait time<br>▪ Component inventory is necessary → some inventory risk remains<br>▪ If production is far away → high shipment costs (for each order) |

# Make-to-Order can work…

- … if customers are patient.
- … customers have a strong preference for variety.
- … production is reasonably quick.
- … leftover inventory is expensive.

# Hybrid Production Systems

- **Mass customization** – each customer's order is unique, customized to her/his exact preference.
- **Assemble-to-order –** a make-to-order system in which a product is assembled from a set of standardized modular components after an order is received.

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# 2023 Operations Management

# INVENTORY MANAGEMENT WITH FREQUENT ORDERS

# THE ORDER-UP-TO MODEL

# Medtronic

- Designer and manufacturer of medical devices
- Well known for cardiac rhythm products, in particular, pacemakers
- Founded in 1949
- More about Medtronic's history

https://www.medtronic.com

# Pacemaker InSync ICD Model 7272

- Inventory held at three levels: manufacturing plants, distribution centers, field locations
- Our focus:
  The distribution center (DC) in Mounds View, Minnesota
- Demand for a pacemaker occurs when it is implanted in a patient via surgery

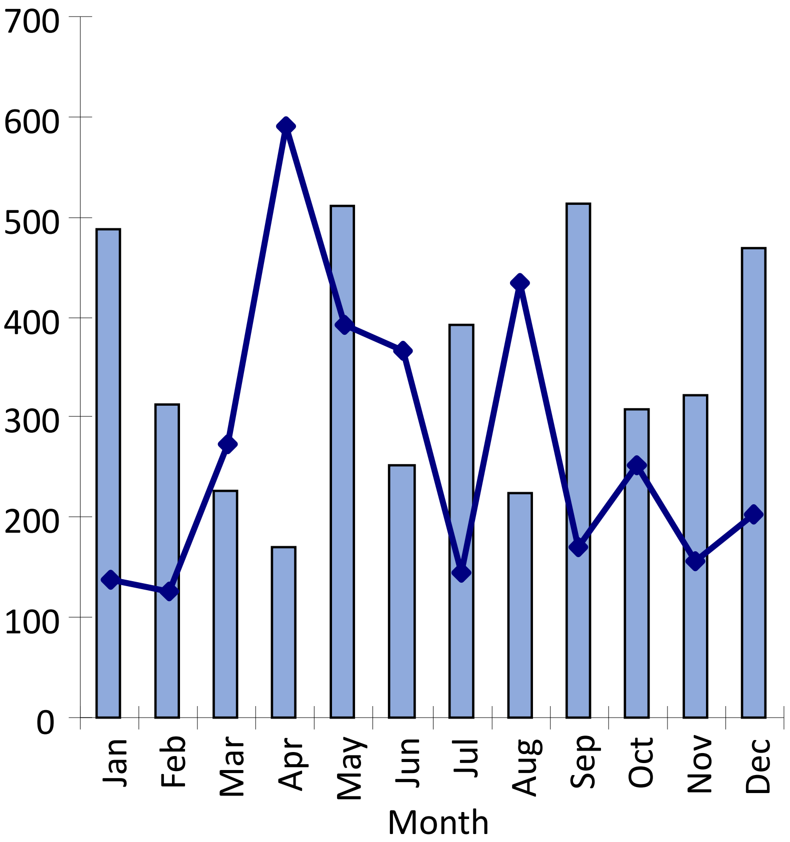

https://www.medtronic.com

# Sales and Replenishment

- Sales representatives attend each surgery and deliver precisely the model that the surgeon requests from their trunk or consignment inventory.
- Sales reps replenish their inventory by calling an order to Medtronic's distribution center. If the requested model is in stock at the distribution center, they receive it typically one day later (rarely more than two days).
- The Mounds View distribution center requests replenishments from the production facilities on a weekly basis. With the InSync pacemaker, there is a three-week lead time to receive an order.

# InSync Demand and Inventory at DC

- Average monthly demand = 349 units
- Standard deviation of monthly demand = 122.4
- Considerable variation
  $CV = \frac{122.4}{349} = 0.35$
- No indication for seasonality

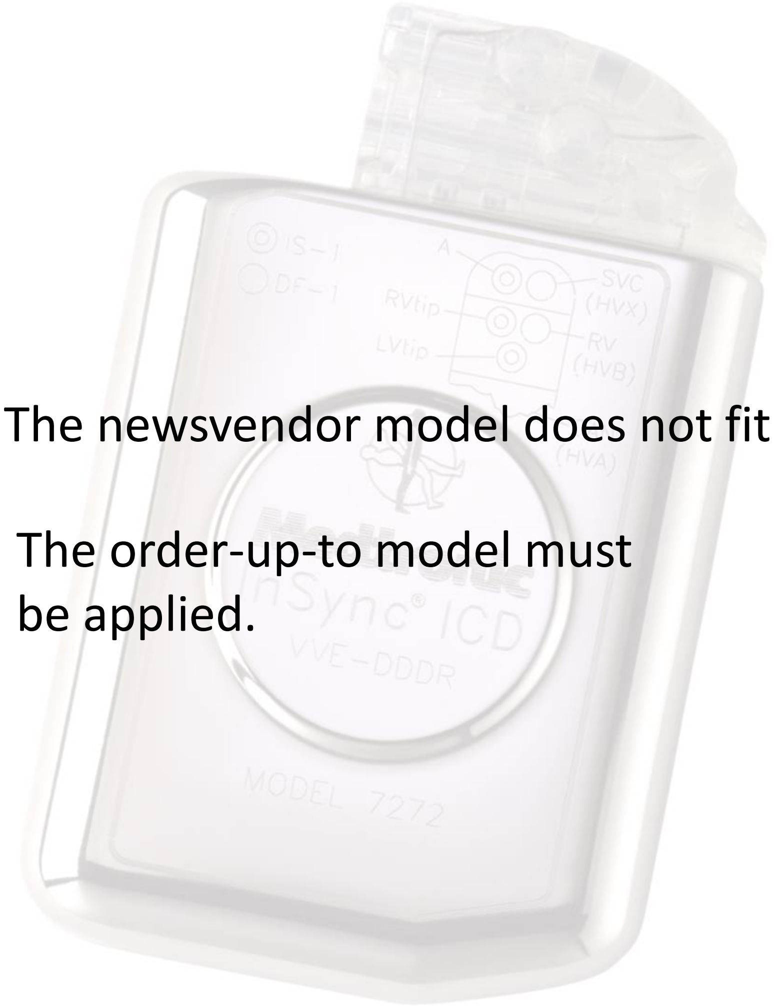



Columns: Demand in units/month
Line: end-of-month inventory in units

# Pacemaker InSync ICD Model 7272 Challenge

- What is the optimal order quantity at the distribution center (DC) in Mounds View, Minnesota?

# Pacemaker Characteristics



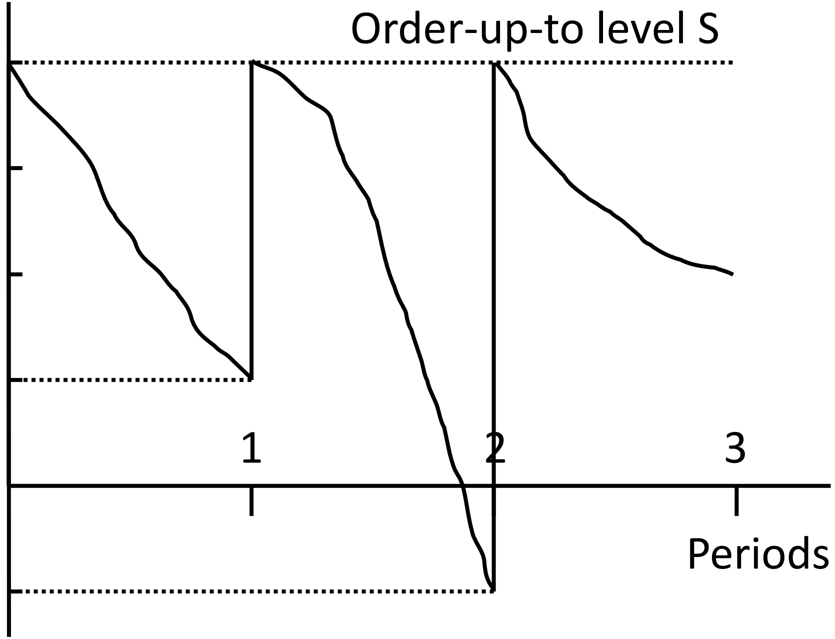

- InSync pacemakers
  - Have very high gross margins
  - Do not perish
  - Have a rather long life cycle and can be replenished multiple times
- Target:
  - Minimize inventory investment while maintaining a very high service target (99.9% in-stock probability)

⇨ The newsvendor model does not fit.

⇨ The order-up-to model must be applied.

# The Order-up-to Model

- Considers a single product that is sold over a long time horizon
- Demand follows a random distribution
- Opportunities to replenish inventory occur in regular time intervals
- Time between two ordering opportunities is called period
- All periods are of the same duration (e.g., one hour, one week, one month)
- Each period’s demand is the outcome of a single random distribution



# Order-up-to Model Terminology

- On-order inventory/pipeline inventory: number of units that have been ordered but have not been received
- On-hand inventory: number of units physically in inventory ready to serve demand
- Backorder: total amount of demand that has not been satisfied
  - All backordered demand is eventually filled; there are no lost sales!
  - Back-ordered demand is fulfilled once inventory is available again
- Inventory level = On-hand inventory – Backorder
- Inventory position = On-order inventory + Inventory level
  = On-order inventory + On-hand inventory – Backorder
- Order up-to level, S
  - maximum inventory position we are allowed, also called base stock level

# Order-up-to Model Implementation

- The implementation of the order-up-to policy is intuitive:
  - Check inventory position at the beginning of the period
  - If inventory position < S (order-up-to level) ⇨ order enough to fill inventory position up to S
- Therefore, each period's order quantity = S – Inventory position
  - Consider a sales rep's trunk inventory of the InSync pacemaker :
    - At the beginning of a period an inventory level of -4 units is observed (4 units are back-ordered)
    - On-order inventory is 1 unit
    - Suppose that the chosen order-up-to level is S = 3
    - How many units should the sales rep order at the period's beginning?
- Note: A period's order quantity = the previous period's demand

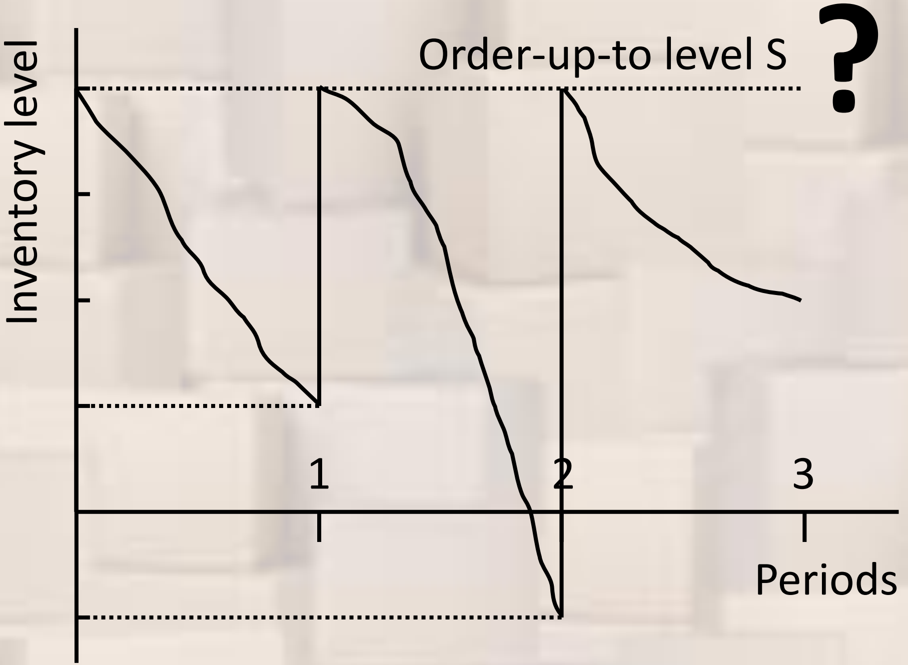
  ⇨ Pull system because inventory is ordered in response to demand

  ⇨ 1-for-1 ordering policy

# How to set the order-up-to level S?

Intuitive relations:

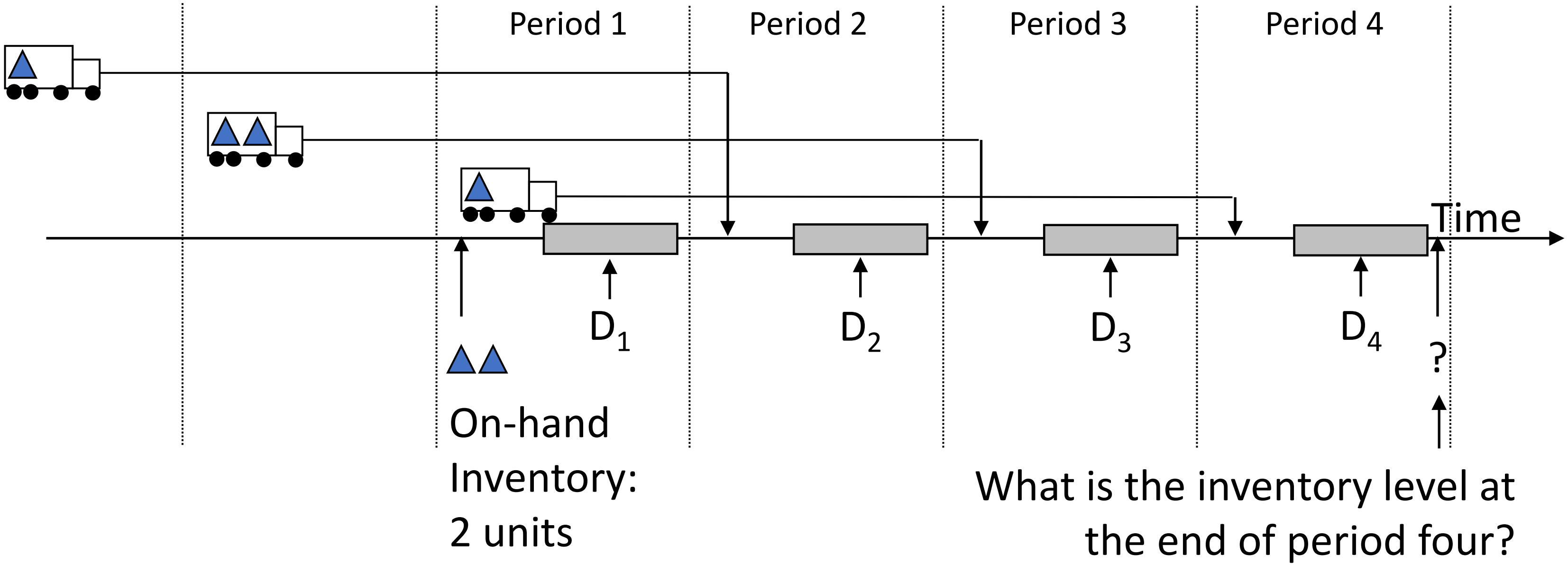
- High S
  - ➪ high inventory level
    - ➪ high service level
      - ➪ high inventory holding costs
- Low S
  - ➪ low inventory level
    - ➪ low service level
      - ➪ low inventory holding costs




➪ Important to understand the inventory level (= on-hand inventory – backorder) in the order-up-to model

# The End-of-Period Inventory Level

Suppose: S = 6, lead time l = 3




What is the inventory level at the end of period four?

It is: $6 - D_1 - D_2 - D_3 - D_4$

# Pacemaker InSync ICD Model 7272 Challenge

Adapted to the order-up-to model:

- What is the optimal order-up-to level at the distribution center if Medtronics service target is 99.9 % in-stock probability?



https://www.medtronic.com

# Order-up-to Level at the Distribution Center

- The Mounds View distribution center requests replenishments from the production facilities on a weekly basis. With the InSync pacemaker, there is a three week lead time to receive an order.
  - one period = one week
  - (production) lead time = three weeks = three periods
- Demand distributions required for
  - one (focal) period and
  - l+1 periods (= 4 periods)

# Distribution Center Demand Distribution

$$Average\ weekly\ demand =$$

$$Std.dev\ weekly\ demand =$$

We know:

- Average monthly demand: 349 units/month
- Std. dev. of monthly demand: 122.38 units/month
- One period = one week
- l+1 periods = 4 weeks

We need to convert demand distribution

- from one long period (months) to
- n short periods (weeks).

We know that there are 52/12 = 4.33 weeks per month.

# Converting a Demand Distribution

From a long period length (e.g., a month) into n short periods (e.g., 4.33 weeks):

$$\mu_{\substack{Demand \\ short\ Period}} = \frac{\mu_{\substack{Demand \\ long\ Period}}}{n}$$

$$\sigma_{\substack{Demand \\ short\ Period}} = \frac{\sigma_{\substack{Demand \\ long\ Period}}}{\sqrt{n}}$$

From n short period length (e.g., 4.33 weeks) into one long period (e.g., a month):

$$\mu_{\substack{Demand \\ long\ Period}} = n \cdot \mu_{\substack{Demand \\ short\ Period}}$$

$$\sigma_{\substack{Demand \\ long\ Period}} = \sqrt{n} \cdot \sigma_{\substack{Demand \\ short\ Period}}$$

The above formulas assume the same demand distribution represents demand in each period and demands across periods are independent of each other.

# 99.9% In-stock Probability at the Distribution Center

- The distribution center is in stock in a period if all demand is satisfied in that period.
- If on-hand inventory at the distribution center is 50 pacemakers at the beginning of a period and demand is 50 units in that period, the center is in stock even though the end of period inventory is 0.
- The center is not in stock if one or more units are backordered at the end of the period, which means that the inventory level at the end of the period is negative.

# 99.9% In-stock Probability at the Distribution Center

- Determine the z-value

- Determine order-up-to level S

$$End\text{-}of\text{-}period\ inventory = S - demand\ over\ l+1\ periods$$

$$In\text{-}stock\ probability = prob(demand\ over\ l+1\ periods \leq S)$$

This formula is a good appproximation for high in-stock probabilities.

$$Order\text{-}up\text{-}to\ level$$
$$S = \mu_{l+1} + z \cdot \sigma_{l+1}$$

$$\mu_{4\ weeks} = 4 \cdot 80.54 = 322.15 \frac{units}{4\ weeks}$$

$$\sigma_{4\ weeks} = \sqrt{4} \cdot 58.79 = 117.58 \frac{units}{4\ weeks}$$

# PERFORMANCE MEASURES

# InSync ICD Model 7272 Challenges II

Suppose that S = 625 at the DC, what is…

- …expected on-hand inventory?
- …in-stock probability?
- …stockout probability?
- …expected on-order inventory?
- …expected back order?




https://www.medtronic.com

# Expected On-hand Inventory

- In general, the following is true:
  On-hand inventory at the end of a period equals the order-up-to level S, minus demand over l+1 periods, or zero, whichever is greater.
- The order-up-to level, S, is like an order quantity in the newsvendor model: it determines the amount of inventory that is available in the system before demand occurs.
- The available inventory is reduced by demand, leaving the firm potentially with some inventory.
- In the newsvendor model, the inventory after demand is called leftover inventory. In the order-up-to model, it is called on-hand inventory.

# Expected On-hand Inventory I


$$S = 625$$

$$\mu_{4\ Weeks} = 322.15\,\frac{units}{4\ weeks}$$

$$\sigma_{4\ Weeks} = 117.58\,\frac{units}{4\ weeks}$$

$$Expected\ on\text{-}hand\ inventory = I(z) \cdot \sigma_{l+1}$$

# Stockout and In-stock Probabilities

- The in-stock probability is the probability all demand is filled in a period:

$$In\text{-}stock\ probability = prob(demand\ over\ l + 1\ periods \leq S)$$

- The stockout probability is the probability at least one unit is backordered in a period

$$\begin{aligned} Stockout\ probability &= prob(demand\ over\ l + 1\ periods > S) \\ &= 1 - prob(demand\ over\ l + 1\ periods \leq S) \end{aligned}$$

# In-stock and Stockout Probabilities at the DC for S = 625

- Step 1: Determine demand distribution parameters for l+1 periods
- Step 2: Evaluate the z-statistic
- Step 3: Use the z-statistic to look up in the standard normal distribution function table the probability the standard normal demand is z or lower.
- Step 4: In-stock probability = F(z) and stockout probability = 1 - F(z)
  - With S = 625, the in-stock probability is 0.9951 → 99.51%
  - With S = 625, the stockout probability is 1-0.9951 = 0.0049 → 0.49%

$$\mu_{4\ weeks} = 322.15 \frac{units}{4\ weeks} \qquad \sigma_{4\ weeks} = 117.58 \frac{units}{4\ weeks}$$

$$z = \frac{S-\mu}{\sigma} = \frac{625 - 322.15}{117.58} = 2.58$$

| z | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 |
|---|---|---|---|---|---|---|---|
| 2.3 | 0.9901 | 0.9904 | 0.9906 | 0.9909 | 0.9911 | 0.9913 | 0.9916 |
| 2.4 | 0.9925 | 0.9927 | 0.9929 | 0.9931 | 0.9932 | 0.9934 | 0.9936 |
| 2.5 | 0.9943 | 0.9945 | 0.9946 | 0.9948 | 0.9949 | 0.9951 | 0.9952 |
| 2.6 | 0.9957 | 0.9959 | 0.9960 | 0.9961 | 0.9962 | 0.9963 | 0.9964 |
| 2.7 | 0.9968 | 0.9969 | 0.9970 | 0.9971 | 0.9972 | 0.9973 | 0.9974 |

# Expected On-order Inventory

- Expected on-order inventory (also pipeline inventory), is the average amount of inventory on order at any given time
- We use Little's law

$$Inventory = Flow\ rate \cdot Flow\ time$$

- to evaluate expected on-order inventory:

$$On\text{-}order\ inventory = \mu_{1period} \cdot l$$

$$\mu_{\substack{weekly \\ demand}} = 80.54\,\frac{units}{week}$$

$$Flow\ time = lead\ time = 3\ weeks$$

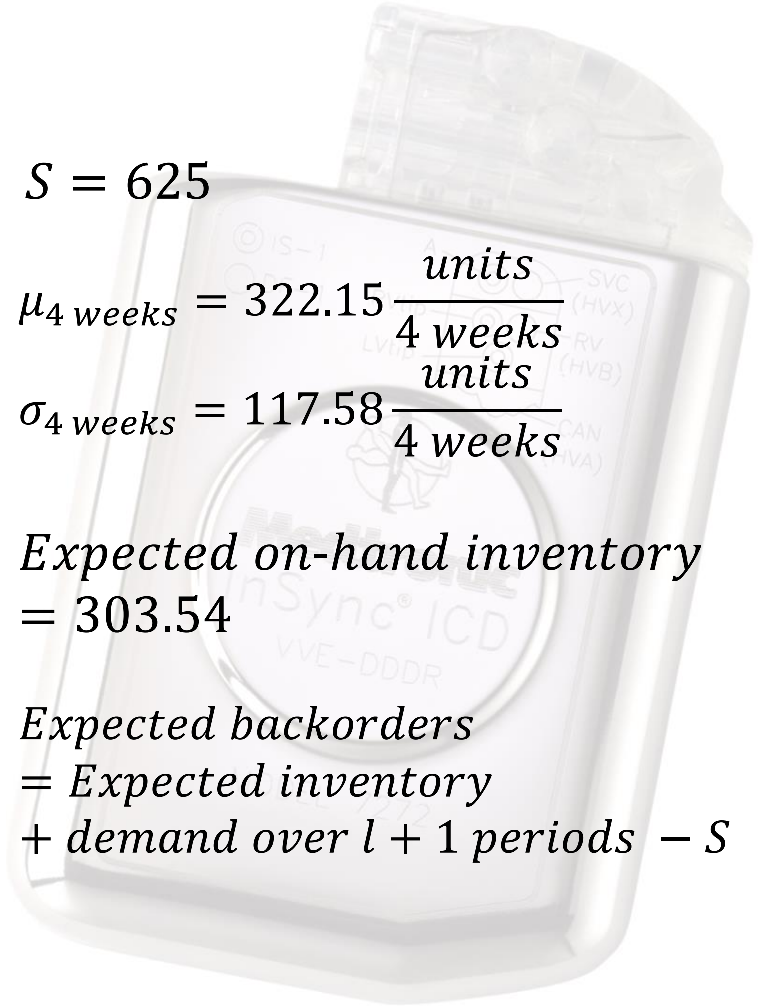
$$On\text{-}order\ inventory =$$

# Expected Back Order

- Expected back order is the expected number of backorders at the end of any period.
- If demand over l+1 periods is larger than S, inventory level at the end of the period is negative (=backorders).

$$Expected\ backorders = Expected\ inventory + demand\ over\ l+1\ periods - S)$$

# Expected Back Order



$$S = 625$$

$$\mu_{4\,weeks} = 322.15\,\frac{units}{4\,weeks}$$

$$\sigma_{4\,weeks} = 117.58\,\frac{units}{4\,weeks}$$

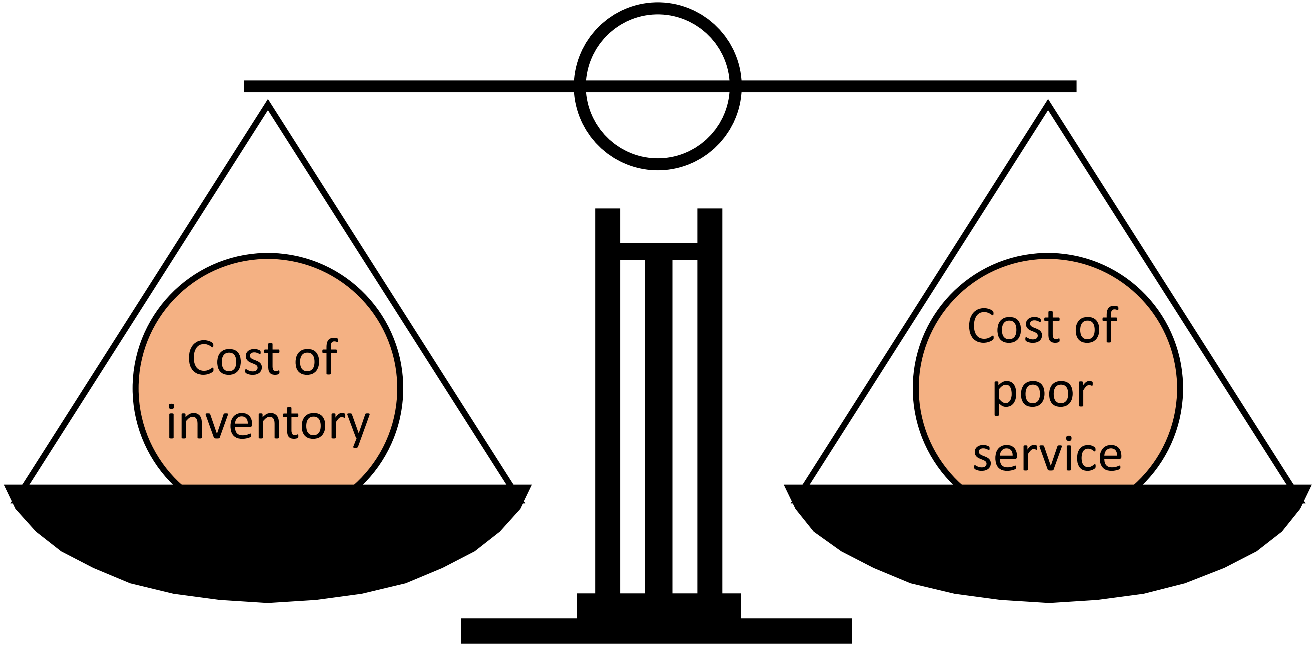
$$Expected\ on\text{-}hand\ inventory$$
$$= 303.54$$

$$Expected\ backorders$$
$$= Expected\ inventory$$
$$+\ demand\ over\ l + 1\ periods\ \ - S$$

# CHOOSING AN APPROPRIATE SERVICE LEVEL

# Choosing an Appropriate Service Level

An appropriate service level minimizes the cost of holding inventory plus the cost of poor service:



# Cost of Holding Inventory

- Holding cost: cost of holding one unit of inventory over one year (as % of the item's cost)
- Suppose annual holding cost rate (h) = 35% and gross margin = 75%
- Then, the (purchase) cost of one unit is
  $(1 - 0.75) \cdot \text{selling price} = 0.25 \cdot \text{selling price}$
- Annual holding cost are then
  $0.35 \cdot 0.25 \cdot \text{selling price} = 0.0875 \cdot \text{selling price}$
- Given 260 days per year, the daily holding cost of an item is:
  $(0.0875 \cdot \text{selling price}) / 260 = 0.000337 \cdot \text{selling price}$

# Cost of Poor Service

- Cost of poor service
  - A natural measure may be the cost of a backorder (b)
  - Often assumed to be the cost of lost sale (i.e., the gross margin)
- Suppose gross margin = 75%
  then, the “backorder penalty cost” is b = 0.75 · selling price

# Choosing an Appropriate Service Level

- "Too-much versus Too-little" challenge
  - S too high → excessive holding cost
  - S too low → excessive backorder costs
- Using the newsvendor logic with $C_O$ = h and $C_U$ = b
  - Newsvendor:
    choose Q such that the critical ratio equals the probability demand ≤ Q
  - Analogously in the order-up-to model:
    choose S such that Prob(Demand over l+1 periods ≤ S)
  - Condition for minimizing holding and backorder costs:

$$Prob(Demand\ over\ l + 1\ periods \leq S) = \frac{b}{b + h}$$

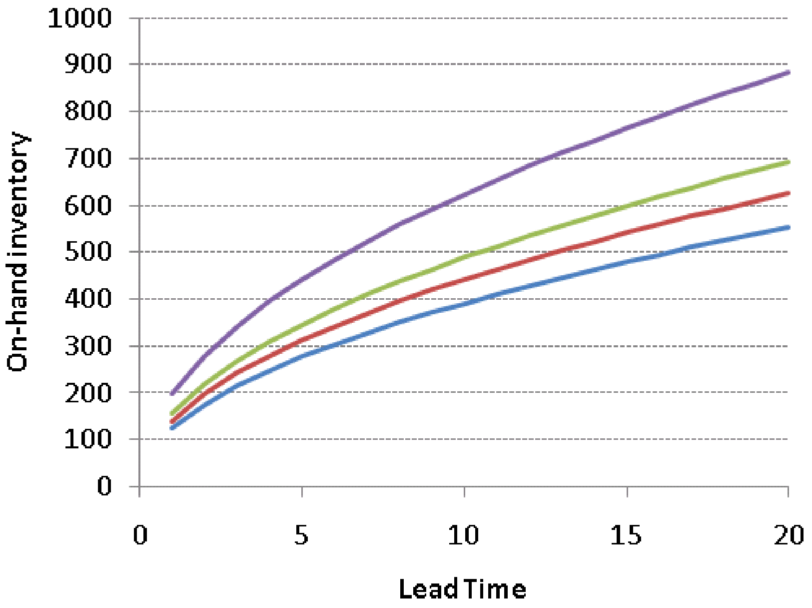
# Optimal Service Level

- Recall:
  - The holding cost in a period of an item: h = 0.000337 · selling price
  - Backorder penalty cost in a period: b = 0.75 · selling price

$$Critical\ ratio = \frac{b}{b+h} =$$

- Note:
  Although holding inventory is not cheap (35%/year), we should maintain an extremely high in-stock probability of 99.96%.

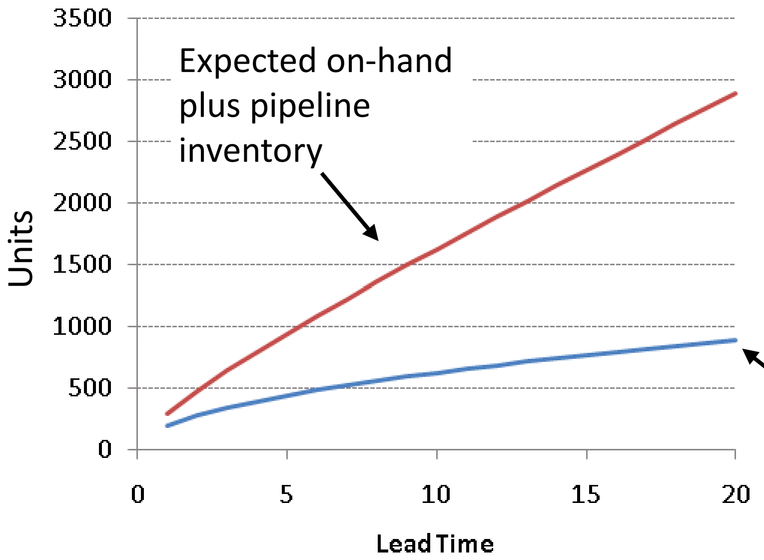
# Shorten lead times and you will reduce inventory




Reducing the lead time reduces expected inventory, especially as the target in-stock increases.

The impact of lead time on expected inventory for four in-stock targets, 99.95%, 99.5%, 99.0% and 98%, top curve to bottom curve respectively. Demand in one period is normally distributed with mean 100 and standard deviation 60.

# Do not forget about pipeline inventory

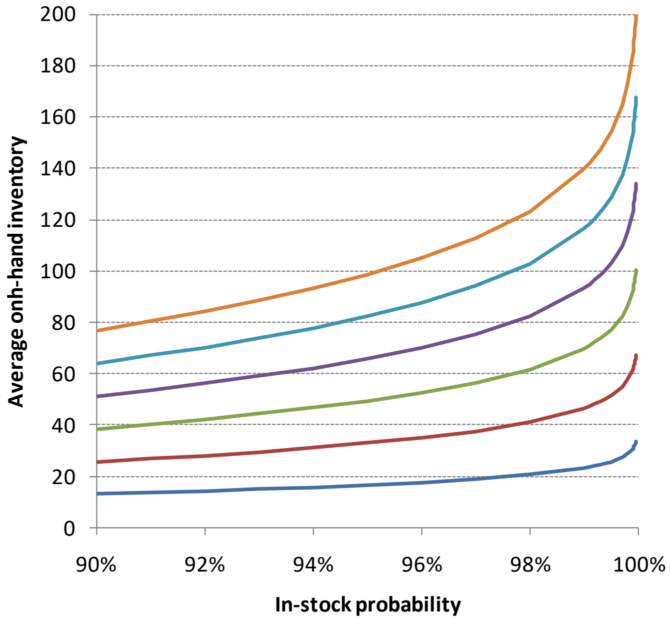



Reducing the lead time reduces expected inventory and pipeline inventory.
The impact on pipeline inventory can be even more dramatic that the impact on expected inventory.

Expected on-hand inventory

99.95% in-stock requirement and normally distributed demand in one period with a mean of 100 and standard deviation of 60.

# Increase service and you need to add inventory




- The higher the targeted service, the more inventory needed.
- Inventory increases at an increasing rate as the target service approaches 100%.
- The higher the uncertainty of demand the more inventory increases with increasing target in-stock probability.

The tradeoff between inventory and in-stock probability with Normally distributed demand and a mean of 100 over (l+1) periods. The curves differ in the standard deviation of demand over (l+1) periods: 60, 50, 40, 30, 20, 10 from top to bottom.

# Order-up-to Model vs. Newsvendor Model

- Both models have uncertain future demand, but there are differences

| | Newsvendor | Order up-to |
|---|---|---|
| Inventory obsolescence | After one period | Never |
| Number of replenishments | One (maybe two or three with some reactive capacity) | Unlimited |
| Demand occurs during replenishment | No | Yes |

- Newsvendor applies to short life cycle products with uncertain demand and the order up-to applies to long life cycle products with uncertain, but stable, demand.

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